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A STUDY OF CORROSION IN MUNICIPAL
INCINERATORS VERSUS REFUSE COMPOSITION

D. A. Vaughan, et al

Battelle Columbus Laboratories

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

In order to better understand the mechanisms of metal corrosion within solid waste incinerators, this study has accumulated a wealth of experimental measurements and data analyses. Hopefully, the distribution and application of these results will lead to more efficiently designed and more economically operated incinerators in future years.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center, Cincinnati

ABSTRACT

Fireside corrosion resulting from the combustion products of municipal and industrial refuse is a severe problem to solid waste disposal by incineration in water-wall furnaces, and/or where heat-recovery systems are employed. Furthermore, with advances in recycling and resource recovery the composition of the burnable portion of the refuse will be altered. Hence, a study was made of the effects of refuse composition on fireside corrosion of nine alloys and two protective coating materials to develop a better understanding of corrosion in solid waste incinerators. The refuse compositional variables investigated were chlorine, which was introduced through the addition of polyvinyl chloride (PVC), and sulfur, which was added in the elemental state. Air-cooled probes exposed to the resulting combustion environments were analyzed for corrosion rates and for deposit composition. Also, the combustion gases were monitored.

CONTENTS

	<u>Page</u>
Abstract	iv
List of Figures	vi
List of Tables	vii
Acknowledgments	viii
<u>Sections</u>	
I Conclusions	1
II Recommendations	3
III Introduction	4
IV Experimental Program	6
Corrosion Probe Design	10
Corrosion Analyses	12
Description of the Alloys and Coatings	13
V Results	14
Corrosion Rates Versus PVC Additions to Refuse	14
Corrosion Rates Versus Sulfur Addition to Refuse	21
Mode of Attack	22
Deposit and Corrosion Product Analysis	29
Furnace and Stack Gas Analyses	33
VI Discussion of Results	37
VII References	40
VIII Appendices	
Appendix A - Corrosion-Probe Data	42
Appendix B - Analyses of Type and Composition of Refuse	47

FIGURES

<u>No.</u>		<u>Page</u>
1	Isothermal corrosion-rate data for A106 steel versus time of exposure to solid-waste combustion products . .	7
2	Sketch of Miami County incinerator, Troy, Ohio	9
3	Schematic of corrosion probe apparatus	11
4	Isothermal corrosion rate of A106 steel versus percent PVC added to refuse	15
5	Isothermal corrosion rate of T11 steel versus percent PVC added to refuse	16
6	Corrosion rate of A106 steel versus metal temperature.	18
7	Corrosion rate of T11 steel versus metal temperature .	19
8	Isothermal corrosion rate for A106 steel versus sulfur additions to refuse	21
9	Photomicrographs of A106 steel showing mode of attack	23
10	Photomicrographs of 446 steel showing mode of attack .	24
11	Photomicrographs of 316 stainless steel showing mode of attack	26
12	Photomicrographs of 310 stainless steel showing mode of attack versus refuse composition	27
13	Photomicrographs of diffusion-bonded coating on A106 steel after exposure to refuse combustion environments	28
14	Chloride concentration in deposit versus amount of PVC added to refuse	31

TABLES

<u>No.</u>		<u>Page</u>
1	Nominal compositions of steels used on corrosion probes	10
2	Results of corrosion-rate analysis versus specimen temperature at various furnace gas temperatures . .	17
3	Results of corrosion-rate analysis versus specimen temperature at various furnace gas temperatures . .	20
4	Chemical assay of deposits versus PVC addition to refuse	30
5	Phase studies of scale next to metal	32
6	Chemical assay of deposits versus sulfur addition to refuse	33
7	Incinerator gas analyses	35
8	Stack gas analyses	35
9	Analysis of particulates collected with furnace and stack gases	36
10	Corrosion data versus PVC additions	43
11	Corrosion data versus sulfur additions	45
12	Type of refuse in grab sample	49
13	Analysis of remixed and ground refuse from grab sample	50

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SECTION I

CONCLUSIONS

The results obtained in this research program show that the sulfur and chlorine contents of refuse have very significant effects on the corrosion of metal surfaces exposed to the hot combustion products. Corrosion was accelerated when the chloride content of the tube deposits increased, as occurred when polyvinyl chloride (PVC) was added to the refuse. However, corrosion rates decreased when the chloride in the tube deposits was replaced by sulfate, as occurred when sulfur was added to the refuse.

The amounts of inorganic chloride or sulfate formed in the tube deposits and in the fly ash were found to be proportional to the amounts of PVC or sulfur added to the refuse. However, the concentration of HCl or sulfur oxides in the flue gases increased, but not in proportion to the additions of PVC or sulfur.

Inasmuch as the chlorine content of normal refuse is high relative to the sulfur content, a small (0.5 percent) addition of PVC produced as much of an increase in the corrosion rates of low-alloy steels at 400-800 F metal temperature as did PVC additions of 1 to 2 percent. At metal temperatures above 900 F the corrosion rates of these steels increased linearly with the amount of PVC added to the refuse. However, the corrosion rates of stainless steels were not affected by the PVC content of the refuse, but increased with furnace-gas temperature.

On the other hand, the addition of sulfur to the refuse produced a sharp decrease in the corrosion rates of all types of steel investigated. In the case of low-alloy steel, the sulfur addition must be sufficient to reduce the chloride content of the deposit to the 0.1 percent level in order to achieve low corrosion rates.

For metal temperatures of 900-1200 F, increasing the furnace-gas temperature from 1400 to 1550 F increased the corrosion rates of both the low-alloy and stainless steels by two to four times. In the case of metal temperatures from 400-800 F, the increase of gas temperature had little effect on the corrosion rates.

It is concluded that through control of refuse composition by additives and/or selection of refuse mixture, the corrosion rates for several of the materials investigated may be held to an acceptable level, providing that the metal temperatures do not exceed 800 F and the furnace-gas temperature does not exceed 1450 F. It is important to note, in addition, that the corrosion rates obtained for 10-hour exposure times cannot be extrapolated to long-time service.

SECTION II

RECOMMENDATIONS

Two general operating procedures were indicated by this research program to minimize corrosion in incinerators using water-cooled tubes in the walls or heat-exchanger tubes in convection passes: (1) It is advisable to process the refuse in such a manner as to avoid high concentration of chlorine and/or to mix into the refuse sufficient quantities of sulfur-bearing refuse to minimize the amount of chloride deposit on tube materials. (2) Care should be taken to maintain metal temperatures well below 800 F and to avoid exposure of tubes, operating at high temperature, to furnace-gas temperatures over 1450 F.

Although the general corrosion rates of all alloys investigated are shown to be significantly lower in short-time exposures by the proper control of refuse composition, metal temperature, and furnace-gas temperatures, additional research is needed:

- (1) Long-term exposures under boiler operating conditions are required to verify the decrease of corrosion rates with time.
- (2) The reduction of corrosion by burning high-sulfur coal fuel with refuse should be investigated.
- (3) Additives other than sulfur to combat chloride attack should be investigated.
- (4) The effect of stress on corrosion of stainless steels at operating temperatures and during downtime should be examined further.

SECTION III

INTRODUCTION

Because increasing attention is being given to the disposal of refuse by incineration as an energy source, we can expect it to become an economical process, but only if the incineration does not create pollution problems. Most of the pollution-control devices require that heat (energy) be extracted to permit operation of the flue-gas cleaning systems. This can be achieved by water-wall tubes and convection pass tubes inserted in the hot gases to absorb the heat. The technology of water-wall incinerators has advanced to a state of rather extensive use in Europe and several are operating in the United States. Corrosion problems have been reported, however, in most of the operating units. Municipal refuse is also being considered as a supplementary fuel to existing fossil fuel power generating stations and for industrial or municipal needs in process steam. To provide guidance in materials selection for both pollution-control and heat-recovery systems, the magnitude of the corrosive attack by the hot gases and deposits has been investigated in a conventional ceramic-lined incinerator operating with municipal refuse.

Under a previous research grant (EP00325) supported by the Solid Waste Management Office of EPA, Battelle investigated the mechanism and extent of fireside metal wastage by incineration of municipal refuse. On the basis of this study, corrosion mechanisms were proposed to explain the attack, which occurred over a range of metal temperatures. These results have been published by the National Environmental Research Center, Cincinnati, Ohio,¹ and in various technical journals.²⁻¹⁰ On the basis of these previous investigations, it was shown that chlorine, as HCl and/or solid chloride deposits, contributes significantly to high- and low-temperature corrosion of structural material in incinerators.

Because of the wide variations in refuse composition and the possibility of adverse effect upon metals employed in heat-recovery systems by these variations, a program was initiated to evaluate specific variables such as chlorine and sulfur. As it is difficult to control refuse collection and/or sort sufficient quantities of classified refuse to maintain operation at an operating incinerator it was concluded that the most feasible approach was to add significant amounts of the variables of interest to the refuse. The increase of HCl and/or chloride content in the combustion products by the addition of PVC to the refuse incinerated was considered to be of potential interest with respect to its effect upon fireside corrosion and with respect to potential problems in disposing of plastic wastes. Although burning of plastics in well-designed incinerators at normal operating temperatures (1700-2000 F) with an excess of air would not be expected to present difficulties, some grate damage has been observed. However, combustion of PVC, which accounts for 15-20 percent of plastic production and approximately 10 percent of the plastic waste, has been reported by Heimburg¹¹ and Fessler, Lieb, and Spohn¹² to cause severe corrosion of furnace components and heat exchangers. Therefore, the initial investigation of refuse composition on fireside corrosion in municipal incinerators was designed to determine the effects of increasing the amount of chlorine in the combustion products by increasing the PVC content of the refuse.

Variations in the amount of sulfur may occur when the amounts of some refuse, such as some plastics, rubber, etc., change, but in general the sulfur content is normally low (0.2 percent) in most refuse. The addition of elemental sulfur appeared to be the most appropriate method of attaining sulfur contents equivalent to that of fossil fuels. Also, there is considerable interest in the combined burning of coal and refuse for power generation as this method has been practiced in Europe for several years and an experiment is being conducted in the United States by Union Electric's Meramec station near St. Louis. However, the objective of this research program was to obtain a better understanding of factors that contribute to the corrosion of structural and energy-recovery systems associated with municipal refuse incinerators.

SECTION IV

EXPERIMENTAL PROGRAM

The experimental program consisted of

- (1) Determining the corrosion rates of boiler tube materials as a function of PVC(C!) or S additions to refuse
- (2) Analyzing deposits and corrosion products
- (3) Analyzing incinerator gas composition
- (4) Analyzing stack gas and particulate composition
- (5) Analyzing the refuse by type and composition.

As it was not feasible to conduct experiments with controlled additions of specific materials (PVC or S) for long periods of time, the program was designed to collect the necessary data and to expose the corrosion probes in 1 working day at the incinerator. Because previous experience with fireside corrosion in municipal incinerators showed, an increasing corrosion rate with decreasing time (Figure 1), the magnitude of attack in short exposure periods was expected to be sufficient to reveal differences as a function of refuse composition. Hence, a short (≤ 10 -hour) exposure time was selected for the investigation of corrosion rate versus induced variables in refuse composition. However, it was necessary to establish corrosion-rate data for the various materials in the short periods of exposure to the normal (no addition) refuse combustion environment. The corrosion-rate data obtained from a 10-hour exposure of A106 steel are included on Figure 1. These short-time experiments are not intended to establish long-term performance, but to show differences in the corrosiveness of the combustion environment, but are applicable where soot blowers remove the semiprotective coating of oxides that develop with exposure time.

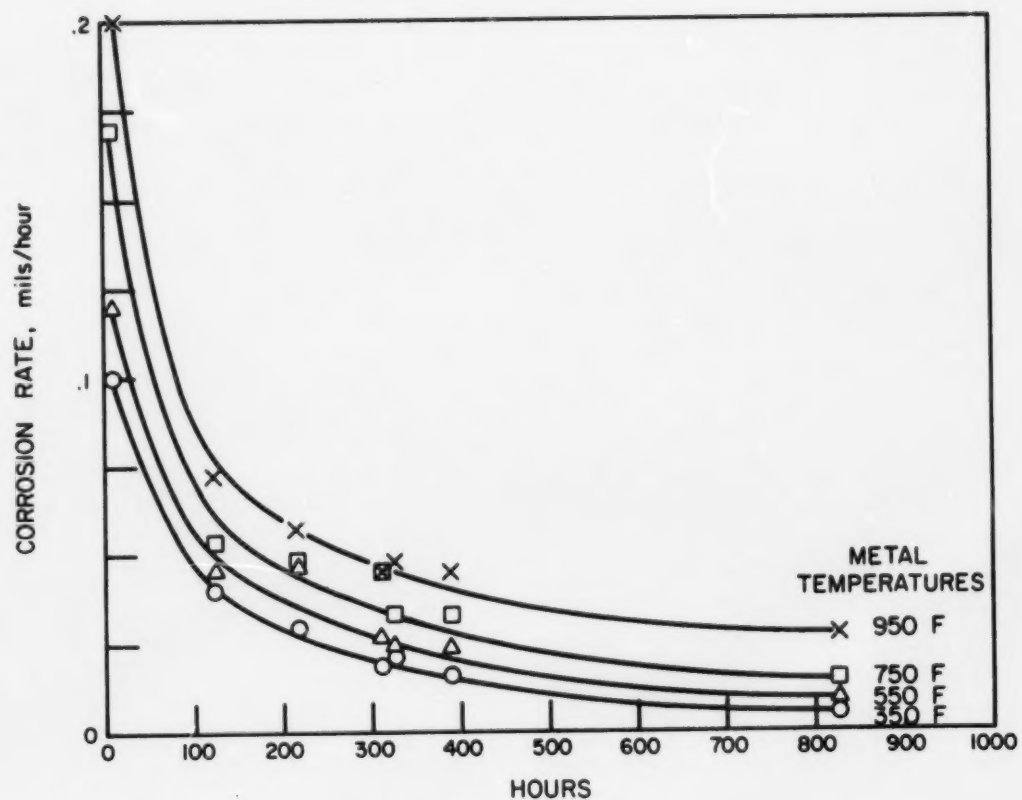


Figure 1. Isothermal corrosion-rate data for A106 steel versus time of exposure to solid-waste combustion products

The above data illustrate the corrosion rates as a function of exposure time and metal temperature - metal temperature being controlled by the internal flow of cooling air through the corrosion probe, which is described later. Also, the effect of furnace-gas temperature variations on the corrosion of heat-recovery tubes, which was monitored during the experiments, was investigated. This was accomplished by inserting corrosion probes, simultaneously, at the two positions shown in Figure 2 where the furnace gas temperatures differed by 100-150 F. Because the operational parameters in the incinerator vary with refuse, it was necessary to average the temperature records over the period of the exposure. During any experiment the gas temperature, as measured near the probe or taken from the incinerator instrument chart record, differed by 100-300 F depending upon location of the corrosion probe. The average temperatures for the seven experiments consisting of 11 probe exposures are tabulated below:

Experiment number	Probe number	Location of probe	Addition, wt %	Average gas temperature	
				Probe, F	Incinerator, F ^a
72-1	16	1	0	(1420) ^b	1290
72-2	17	1	2-PVC	(1440) ^b	1310
72-3	18	1	1-PVC	(1730) ^b	1600
72-4	19	1	0.5-PVC	1400	1260
72-4	20	2	0.5-PVC	(1550) ^c	1260
73-1	21	1	0	1420	1340
73-1	22	2	0	1660	1340
73-2	23	1	1.5-S	1420	1300
73-2	24	2	1.5-S	1510	1300
73-3	25	1	0.75-S	1440	1310
73-3	26	2	0.75-S	1550	1310

^a The incinerator temperature is that recorded on instrument panel from a permanently installed thermocouple.

^b Estimated from incinerator versus probe measured temperatures.

^c The thermocouple attached to probe failed but an auxiliary thermocouple inserted in the furnace at this location gave the reported value.

It is evident that the furnace gas temperature, as measured by thermocouples extending through the probes, differs significantly from that obtained on the chart record of the incinerator instrument panel. This is undoubtedly a result of thermocouple location and position of overfire air entry ports. However, where two probes were inserted marked differences in temperature were measured. This difference in gas temperature resulted in some variations in the temperature of corresponding specimens of any two corrosion probes.

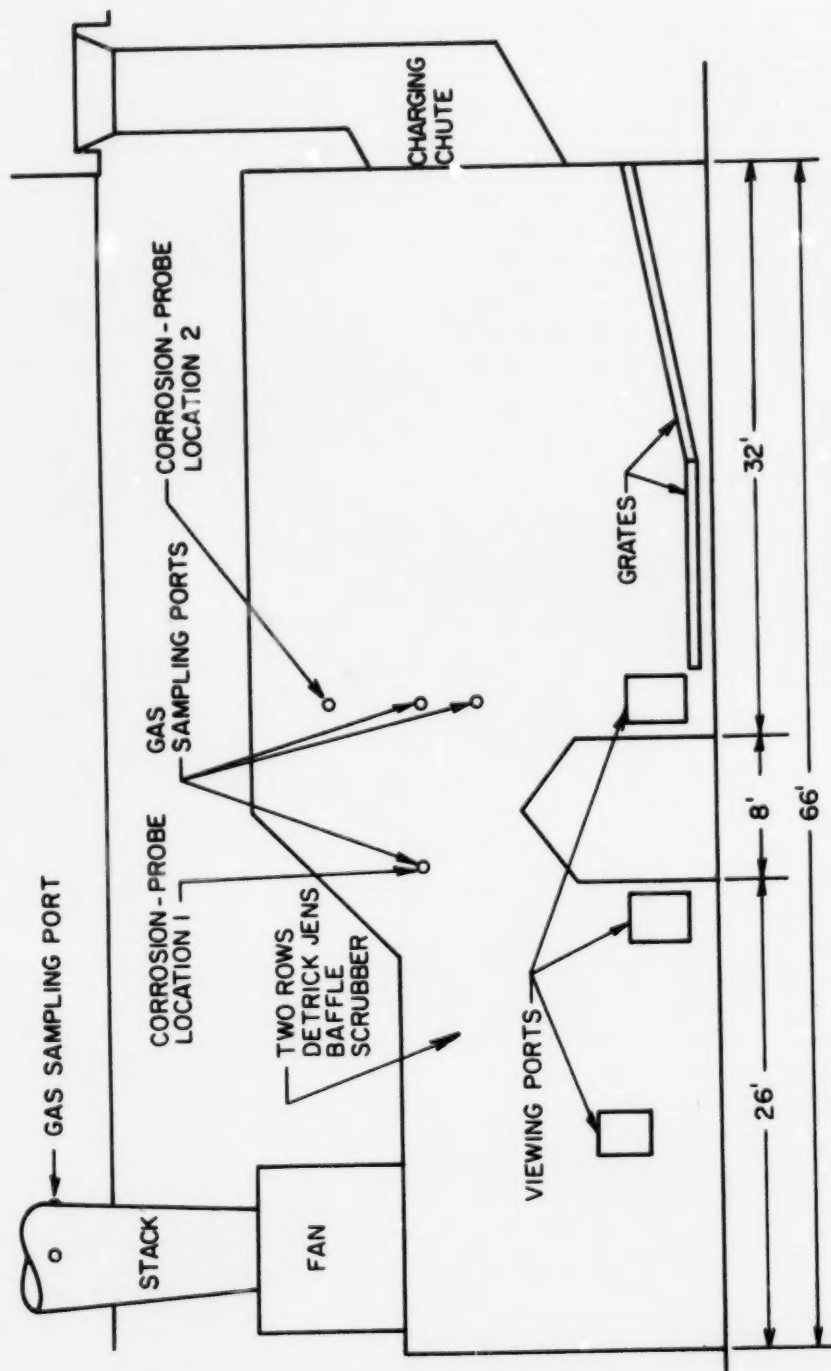


Figure 2. Sketch of Miami County incinerator, Troy, Ohio

Scale: 1/8 inch = 1 foot.

CORROSION PROBE DESIGN

The probe was designed to include 34 cylindrical specimens nested together end to end and then inserted into the incinerator through a side wall. The section of the probe extending through the wall was water cooled, while the specimens exposed within the furnace were cooled by air flowing inside the tubular specimens. A computer analysis had been used in a previous program to ascertain the geometry of the internal support tube required to give the most linear specimen temperature variation over the range of about 350 to 1300 F for a probe with 34 specimens. Each specimen was about 1.25 inches in OD, 1.00 inch in ID, and 1.5 inches long. The composition of the alloys used to make up the corrosion probes is given in Table 1.

Table 1. NOMINAL COMPOSITIONS OF STEELS USED ON CORROSION PROBES

Alloys	Composition of steels, weight percent									
	C	Cr	Ni	Si	Mn	Mo	Ti	Cu	P	S
A106 Grade B ^a	0.30	--	--	0.10	0.65	--	--	--	0.48	0.058
A213-T11	0.15	1.0-1.5	--	0.75	0.5	0.5	--	--	0.03	0.03
316	0.07	17.4	12.2	0.36	2.0	2.12	--	--	0.08	0.01
203 EZ	0.05	16.6	5.5	0.37	5.8	0.15	--	1.9	0.02	0.31
310	0.15	24-26	19-22	0.75	2.0	--	--	--	0.04	0.03
321	0.08	17-20	9-13	0.75	2.0	--	0.60	--	0.03	0.03
Incoloy 825	0.03	21.5	42.0	0.25	0.5	3.0	--	2.25	--	--
431	0.15	16.0	2.2	0.34	0.6	0.16	--	--	0.02	0.01
446	0.11	27.2	0.3	0.47	1.1	--	--	--	0.02	0.02

^a Specimens of this steel were coated with Cr or FeAl by plasma spray and diffusion heat treated at 2150 F or 1885 F, respectively, to produce metallurgical bond and surfaces to be corrosion evaluated.

Figure 3 is a schematic of the final exposure-probe apparatus. The specimens were nested together with lap joints, as shown in Detail A, and retained axially at the cooling-air-outlet end by a retainer which was fixed to the internal support tube with webs as shown in Section A-A. The axial restraining force in the internal support tube was obtained by compressing the spring on the air-inlet end of the probe at assembly. Also, the spring compensated for differential thermal expansion between the specimens and the internal support tube.

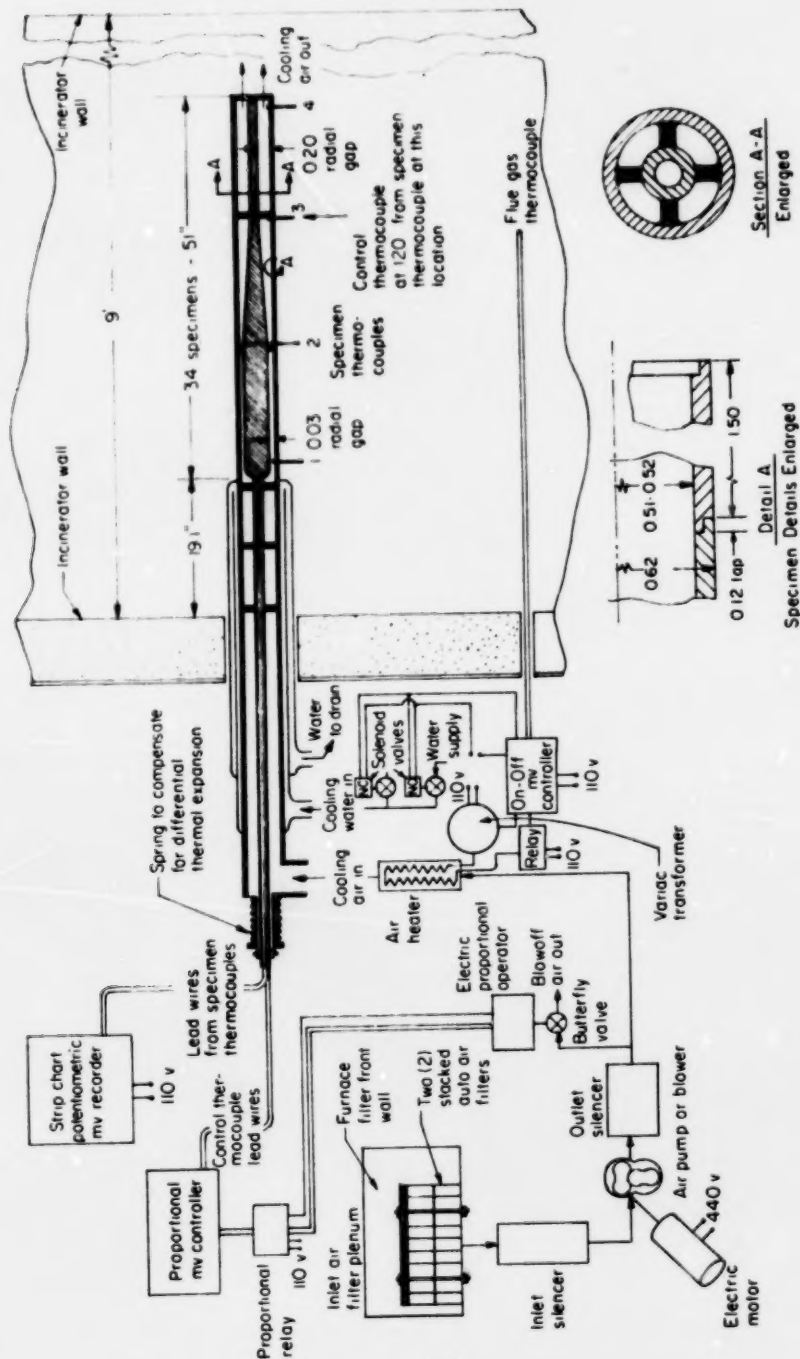


Figure 3. Schematic of corrosion probe apparatus

Specimen temperatures were measured at four stations with Type K thermocouples either welded into the wall of the specimens or inserted into recesses drilled lengthwise into one end of the appropriate specimens. The thermocouple lead wires were brought out of the probe through the center of the internal support tube, so that temperatures could be recorded continuously on a strip-chart potentiometer recorder. Since the computed results indicated that the temperature variation is linear for regions with a constant gap between the internal support tube and the specimens, the four temperatures accurately reflect the specimen temperatures.

The specimen temperatures were controlled by regulating the amount of cooling air admitted to the probe. The output from a control thermocouple, which was attached to the specimen at the same axial location as Thermocouple 3, was monitored by a proportional temperature controller. At the start of a test, the controller maintained this temperature by varying the amount of cooling air bypassing the probe through a motorized butterfly valve located between the blower and the probe. A Roots-blower air pump delivering up to about 34 cfm was used with a 5-horsepower motor as a drive.

Although the temperature of corresponding specimens varied from one probe to another, the specimen temperature employed in the analysis of corrosion-rate data was obtained by interpolation of temperatures recorded for Specimens 1, 9, 17, 27, and 34 on each probe. The interpolated temperature for each specimen on the several probes is tabulated in Appendix A, along with the measured weight loss and the calculated corrosion-rate data.

Corrosion Analyses

Corrosion rates were determined for most of the 34 specimens on each of the 11 probe experiments by comparing the initial weight with that obtained after removal of the corrosion products. The 34 corrosion specimens were first separated from each other by tapping with a fiber mallet. Then the amount of metal wastage was determined by chemically or electrochemically stripping the residual deposits and scale from each specimen using standard procedures. The specimens of T11 and A106 were stripped cathodically in 10 percent H_2SO_4 containing 1-ethylquinolinium iodide inhibitor, while the stainless steel specimens were descaled in a two-step process, first with 11 percent NaOH and 5 percent KMnO_4 at 212 F and then with 20 percent HNO_3 with 2 percent HF at 130 F. These methods of scale removal were employed

to avoid attack of the uncorroded substrate metals. Then the weight loss and dimensional changes were calculated as shown in Appendix A. Prior to removal of the corrosion products and the deposits, optical and X-ray diffraction studies were made of the scale and deposit on several specimens to determine what phase changes occurred as a result of the type or the amount of addition to the refuse. Also, representative specimens were sectioned and examined metallographically to determine the mode of attack by the combustion environments.

DESCRIPTION OF THE ALLOYS AND COATINGS

Most of the alloys (Table 1) were available as tubes from which the (1.25-inch-OD x 1-inch-ID x 1.5-inch-long) specimens were cut and machined to a lap fit. In some cases only rod material was available. The machined specimens were degreased in acetone and rinsed with alcohol, air dried, and weighed before assembling on the corrosion probe. For the experiments run in 1972 all of the specimens were exposed in the as-machined and cleaned condition, except for one experiment in which a representative specimen of each alloy was preoxidized at 1150 F for 1/2 hour in air before making the probe assembly. During the 1973 experiments the specimens of 316 stainless steel were heat treated for 3 hours at 1200 F and 100 hours at 1550 F to stabilize the material against sensitization during exposure to the hot incinerator gases. Also, two types of coatings (Cr or FeAl) were applied by a plasma spray to specimens of the low-alloy A106 steel. These coatings were metallurgically bonded to the base steel by heating in vacuum to high temperatures (2150 and 1880 F, respectively) for 10 hours. After the diffusion treatment, the coated specimens were wire brushed to remove any loose deposit, weighed, and assembled on the probes.

SECTION V

RESULTS

CORROSION RATES VERSUS PVC ADDITIONS TO REFUSE

As mentioned previously, the magnitude of the attack of the various steels when exposed for 10 hours to the combustion products of refuse with 0, 0.5, 1, and 2 percent additions of PVC is presented in Appendix A, Table 10. In this table the total weight loss and the corresponding thickness (mils) of metal wastage plus the rate of attack in mils per hour are given for each specimen. From these data, isothermal corrosion rates of the low-alloy carbon steels were determined as a function of the amount of PVC added to the refuse, the results of which are shown in Figures 4 and 5. A significant increase in corrosion rate of these steels occurred with the addition of 0.5 percent PVC to the refuse. Further increases in the amount of PVC had little or no effect at low (<700 F) specimen temperature, but as the specimen temperature exceeded 900 F the corrosion rate increased linearly with the amount of PVC added to the refuse. Correction for furnace-gas temperature, which varied considerably between experiments, reduced somewhat the magnitude of the corrosive effect of the PVC addition but did not alter significantly the general behavior.

In the case of the stainless steels (316, 310, 321 and 446) and Incoloy 825, however, the corrosion rates were not significantly affected by the PVC content of the refuse. The corrosion rates for these alloys were not affected by specimen temperature but, as tabulated below, an increase in the furnace-gas temperature by 150 F resulted in a large increase in corrosion rate:

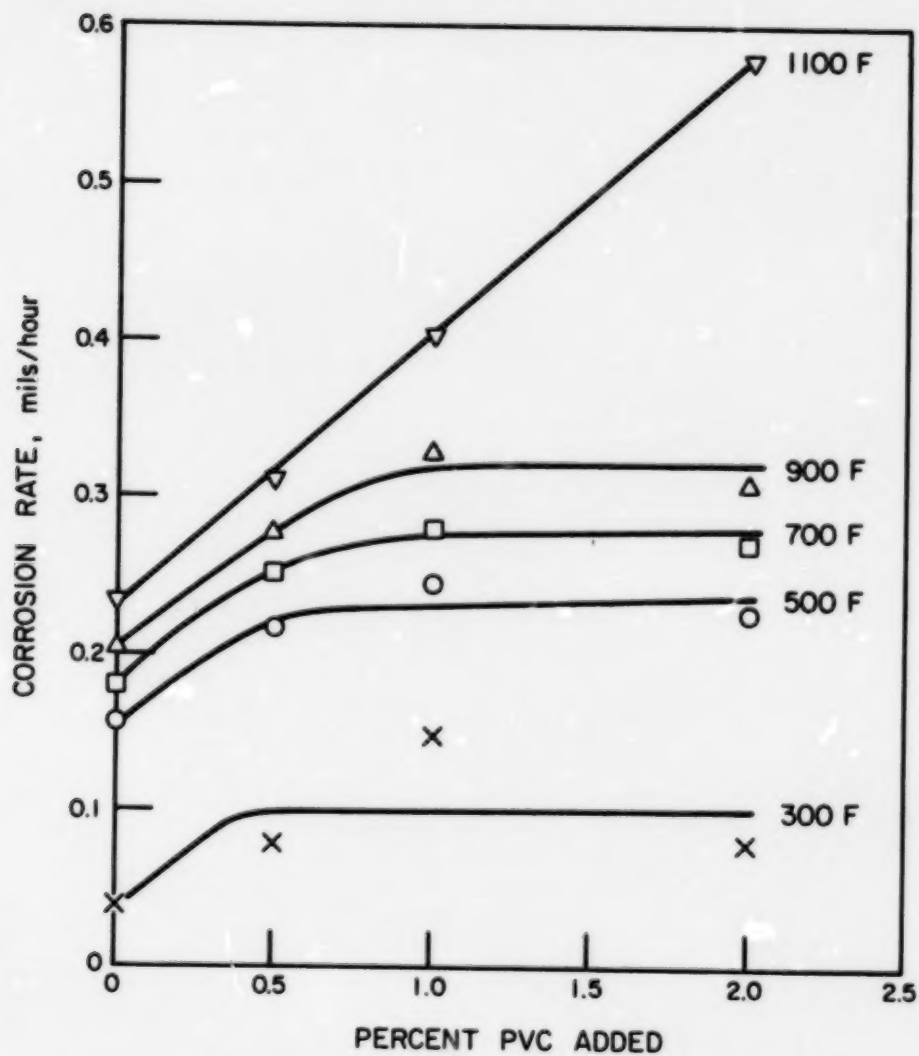


Figure 4. Isothermal corrosion rate of A106 steel versus percent PVC added to refuse

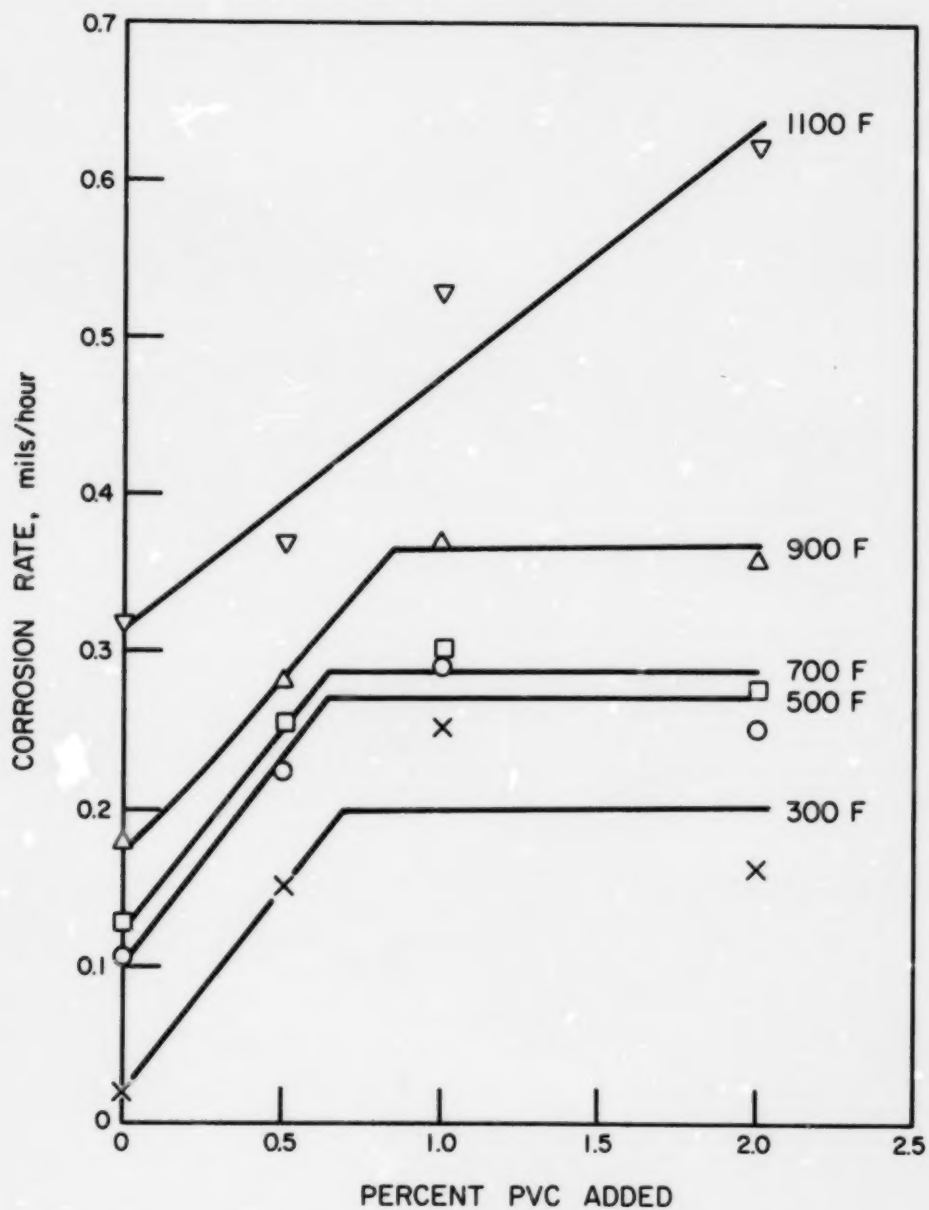


Figure 5. Isothermal corrosion rate of T11 steel versus percent PVC added to refuse

Alloy	Average corrosion rate, mils/hr	
	1400 F Gas	~1550 F Gas
310	0.032	0.170
446	0.050	0.136
825	0.056	0.259
316	0.056	0.203
321	0.109	0.201

These high-alloy steels were held at specimen temperatures of 800-1200 F. However, the corrosion rates of low-alloy steels (A106 and T11) varied with furnace-gas temperature, as shown by the data presented in Figures 6 and 7. The effect of furnace-gas temperature upon the corrosion rates of low-alloy steels is essentially insignificant for specimen temperature below 800 F where these materials would be employed, but for metal temperature above 800 F the furnace-gas temperature has a very marked effect upon the corrosion rate of the low-alloy steels. To show the strong interaction between specimen temperature and furnace-gas temperature as well as refuse composition, the results of the corrosion-rate analyses are presented in Tables 2 and 3. The data are presented for the same specimen temperatures along with the experimental conditions for each probe run. Because the temperature of corresponding specimens on the various probes differed (as shown in Appendix A along with the corrosion-rate data), the data given in Tables 2 and 3 were obtained by interpolation of corrosion rate versus temperature curves. The results on materials exposed to the combustion environment of normal and PVC-doped refuse are shown in Table 2 while those for materials exposed to both PVC and/or S-doped refuse are included in Table 3.

Table 2. RESULTS OF CORROSION-RATE ANALYSIS VERSUS SPECIMEN TEMPERATURE AT VARIOUS FURNACE GAS TEMPERATURES (normal and PVC doped refuse)

Alloy	Furnace-gas temp, F ^a	Refuse addition: None Temp, F (1420)	0.5% PVC		1% PVC	2% PVC
			1400	1500	1730	(1440)
			Corrosion rate, mils/hour			
T11	300	0.02	0.14	0.10	0.24	0.16
	500	0.10	0.23	0.20	0.27	0.25
	700	0.12	0.25	0.25	0.30	0.27
	900	0.18	0.28	0.36	0.37	0.36
	1100	0.33	0.32	0.71	0.54	0.60
825	700	--	0.10	0.10	0.08	0.02
	1100	0.07	0.05	0.28	0.24	0.06
321	1100	0.08	0.14	0.29	0.19	0.13
310	1100	0.023	0.03	0.20	0.15	0.05

^a Temperatures in parentheses were estimated based upon incinerator chart record.

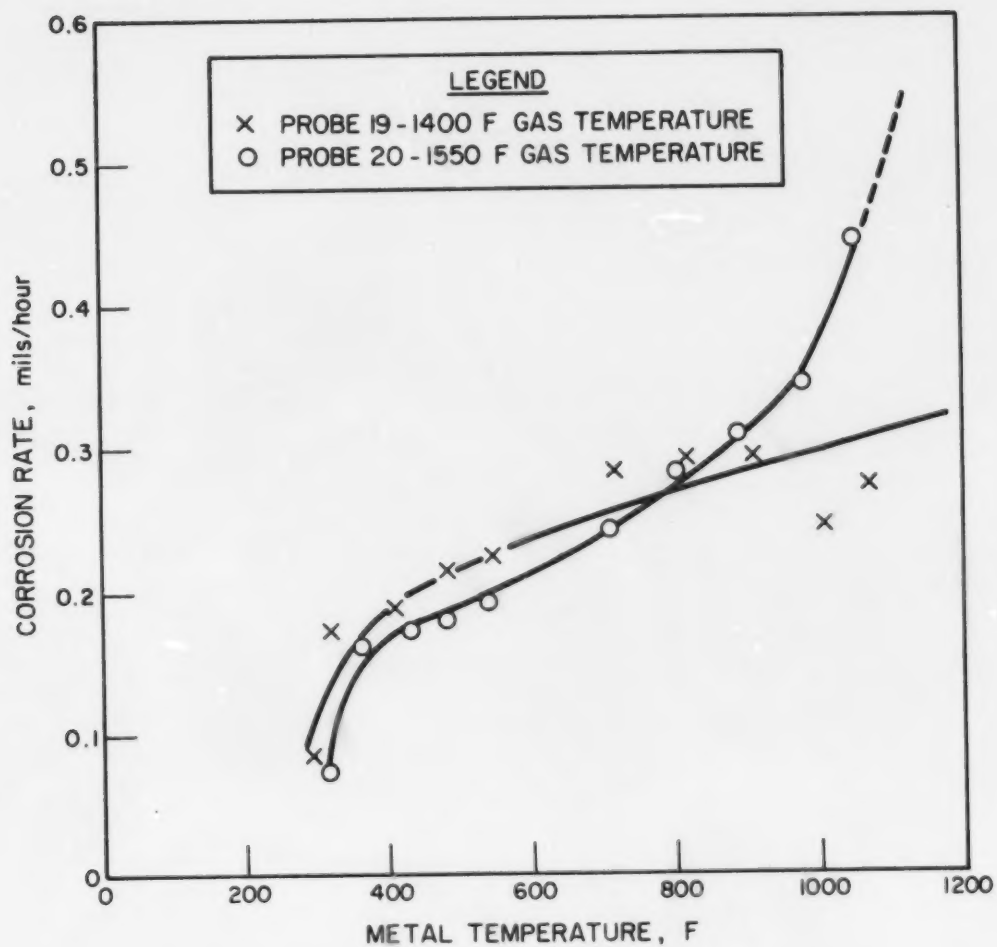


Figure 6. Corrosion rate of Al06 steel versus metal temperature

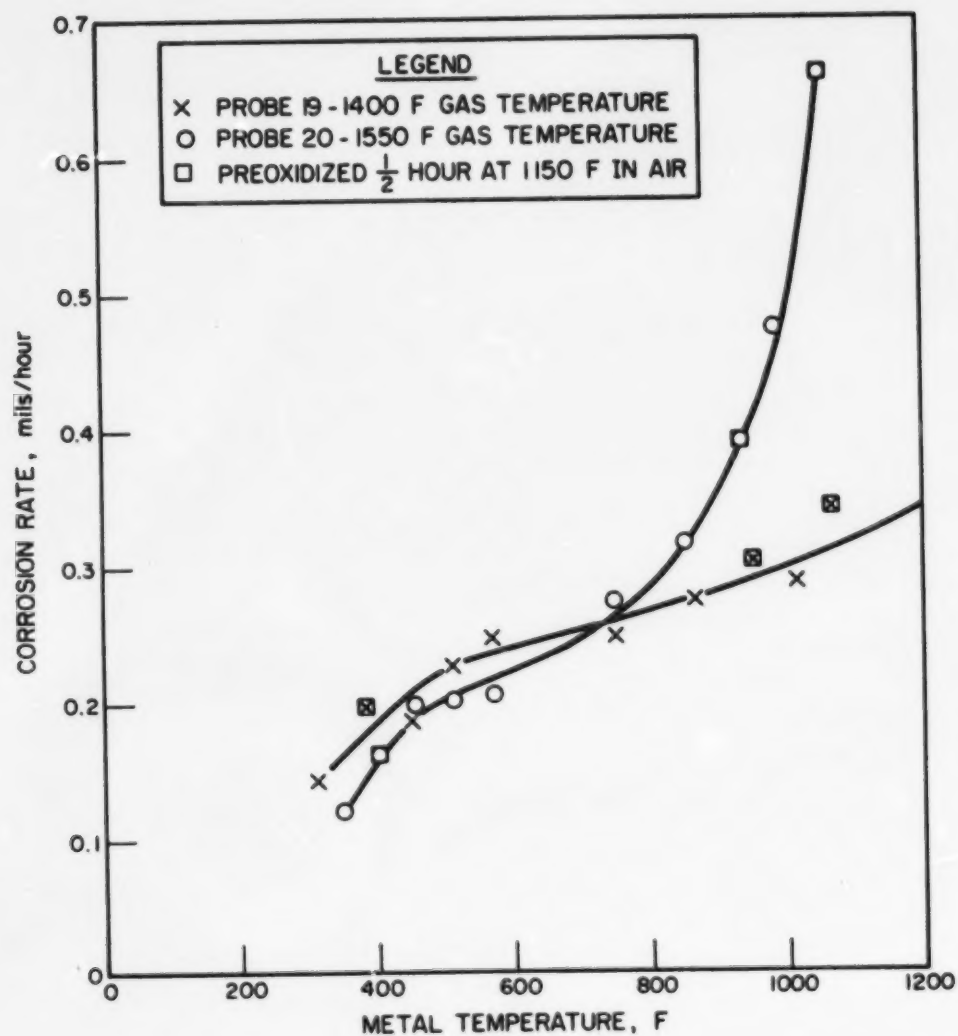


Figure 7. Corrosion rate of T11 steel versus metal temperature

Table 3. RESULTS OF CORROSION-RATE ANALYSIS VERSUS SPECIMEN TEMPERATURE
AT VARIOUS FURNACE GAS TEMPERATURES
(normal, PVC and/or S doped refuse)

Alloys	Refuse addition:		None		0.5% PVC		1.0% PVC		2.0% PVC		0.75% S		1.5% S	
	Furnace-gas temp, F ^a :		(1420)		1400		(1750)		(1440)		1440		1420	
	Temp, F		1480	1660	Corrosion rate, mils/hour									
A106	300	0.05	0.11	0.13	0.11	0.10	0.15	0.10	0.10	0.05	0.14	0.01	--	--
	500	0.16	0.19	0.17	0.22	0.19	0.24	0.23	0.23	0.15	0.26	0.05	0.08	0.08
	700	0.18	0.22	0.24	0.25	0.23	0.28	0.27	0.27	0.22	0.34	0.07	0.09	0.09
	900	0.20	0.28	0.37	0.28	0.31	0.34	0.33	0.33	0.24	0.39	0.09	0.11	0.11
316SS	1100	0.23	0.42	0.69	0.31	0.51	0.43	0.55	0.55	0.32	0.53	0.12	0.22	0.22
	700	--	0.04	0.01	--	--	--	--	--	0.005	0.02	0.005	0.01	0.01
	900	--	0.14	0.09	--	--	--	--	--	0.006	0.02	0.009	0.012	0.012
	1100	0.06	0.23	0.17	0.12	0.25	0.18	0.07	0.07	0.010	0.03	0.015	0.028	0.028
203EZ	700	--	0.155	0.10	--	--	--	--	--	0.040	0.050	0.015	0.020	0.020
	900	--	0.17	0.125	--	--	--	--	--	0.040	0.050	0.020	0.020	0.020
	1100	--	0.185	0.15	--	--	--	--	--	0.045	0.060	0.060	0.030	0.030
	700	--	0.16	0.43	--	--	--	--	--	0.025	0.055	0.005	0.025	0.025
446	900	--	0.125	0.25	--	--	--	--	--	0.025	0.055	0.010	0.025	0.025
	1100	--	0.19	0.165	--	--	--	--	--	0.05	0.065	0.015	0.035	0.035
	700	--	0.07	0.05	0.11	0.09	0.20	0.09	0.09	0.03	0.05	0.003	0.01	0.01
	900	0.05	0.07	0.06	0.07	0.11	0.20	0.09	0.09	0.03	0.055	0.004	0.01	0.01
Cr coated ^b	1100	0.05	0.07	0.06	0.03	0.13	0.20	0.09	0.09	0.03	0.06	0.005	0.01	0.01
	700	--	0.10	0.14	--	--	--	--	--	0.07	0.17	0.005	0.02	0.02
	900	--	0.15	0.15	--	--	--	--	--	0.07	0.17	0.01	0.02	0.02
	1100	--	0.22	0.16	--	--	--	--	--	0.07	0.20	0.015	0.02	0.02
Al coated ^b	700	--	0.105	0.20	--	--	--	--	--	b	b	0.025	0.01	0.01
	900	--	0.125	0.31	--	--	--	--	--	b	b	0.025	0.015	0.015
	1100	--	0.25	0.50	--	--	--	--	--	b	b	0.045	0.03	0.03
	700	--	0.10	0.14	--	--	--	--	--	0.07	0.17	0.005	0.02	0.02

^a Furnace temperatures in () are estimated from incinerator records while the others were measured at probe locations.

^b Some spalling of the Al and Cr coatings caused error in corrosion rate analyses, numbers shown are maximum and include spalling losses.

CORROSION RATES VERSUS SULFUR ADDITION TO REFUSE

The results of the corrosion-rate analysis for the alloys and coated specimens exposed to the combustion products of refuse with 0, 0.75, and 1.5 percent sulfur additions are included in Table 3. The data were obtained in the same manner as described above. Individual specimen-corrosion measurements are presented in Appendix A, Table 11, along with the respective specimen temperature for each probe. The analysis shows that when the sulfur content of the refuse is increased by an addition of 1.5 percent the corrosion rates for all of the materials evaluated decrease by a very significant factor, as much as an order of magnitude for some materials. Also, a significant reduction in corrosion rate of the stainless alloys occurred by the addition of 0.75 percent sulfur. However, when the lower (0.75 percent) amount of sulfur was added to the refuse a slight increase in the corrosion rate of the low-alloy (A106) steel was observed, as shown in Figure 8. Also shown on this graph is the marked decrease in corrosion rate with a further increase in the sulfur content of the refuse.

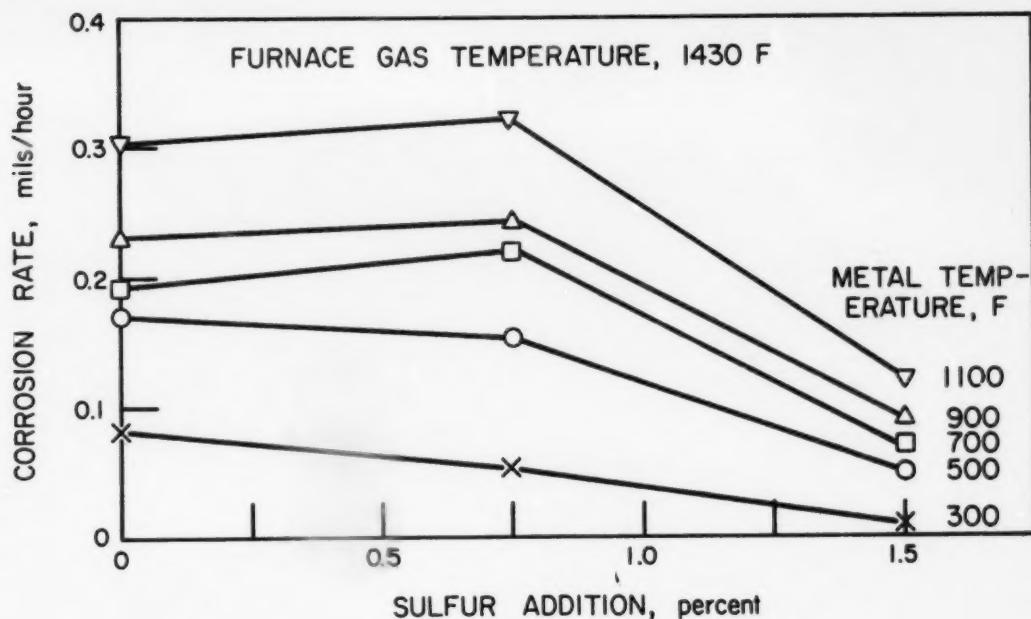


Figure 8. Isothermal corrosion rate for A106 steel versus sulfur additions to refuse

In general the addition of sulfur to refuse appears to reduce the corrosiveness of the combustion products through a modification in the compounds deposited. As described later, the major change in these deposited compounds is the reduction in the amount of inorganic chloride in the deposit with the sulfur addition. In contrast, the addition of PVC increases the chloride content of the deposit and the corrosion rates are increased as shown in Figures 4 and 5.

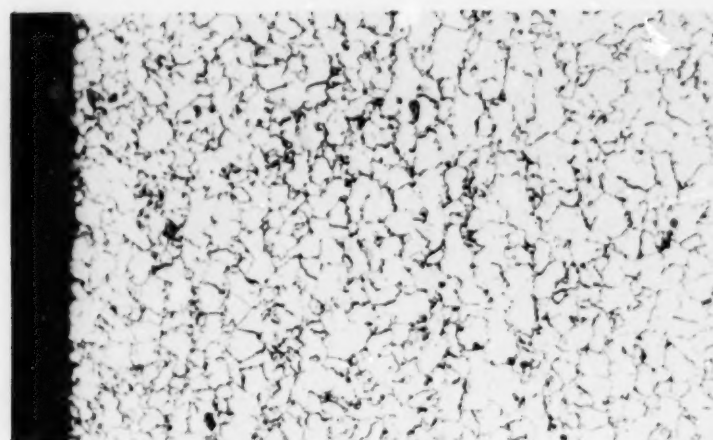
MODE OF ATTACK

The previous two sections describe the magnitude of attack of various steels in terms of refuse composition and the temperatures of the metal and the furnace gases. However, it is important to establish whether the attack is uniform or localized at specific sites in the metal structure. Hence, metallographic examinations have been made of the several alloys and coatings described in Table 1, after exposure to the various environmental conditions produced by combustion of refuse of normal and modified compositions. The results of these examinations are given below by material, and Figures 9-13 are representative photomicrographs.

A106 low-carbon steel exhibits general attack, with some evidence of pitting when exposed to normal refuse, as shown in Figures 9A and 9B which are typical of two metal temperatures, zones 400-800 F and 900-1300 F, respectively. The higher metal temperature produces some surface decarburization as well as internal microstructural changes. When PVC was added to the refuse similar attack was observed with more severe pitting. However, the addition of sulfur essentially eliminates the pitting attack as shown in Figure 9C and, as the weight loss data show, reduces the general attack by a factor of six.

A213-T11 steel was attacked in the same manner as A106 in normal and PVC-enriched refuse, but was not included on the corrosion probe when sulfur was added to the refuse.

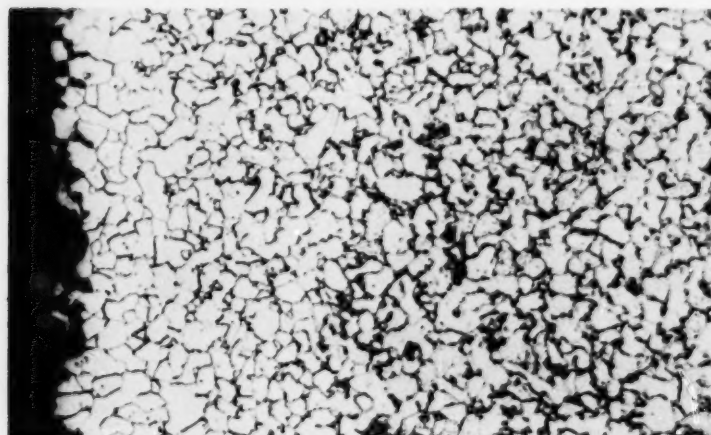
Specimens of 446 steel exposed to normal refuse were attacked at grain boundaries, as shown in Figure 10a. Figure 10b illustrates the type of attack that occurred when PVC was added to the refuse. While the latter appeared to have a more irregular attack than is seen in Figure 10a, the magnitude of the weight loss was essentially the same. The addition of sulfur to the refuse greatly reduced the amount of the general attack and eliminated the intergranular dissolution, as shown in Figure 10c.



C4376

250X

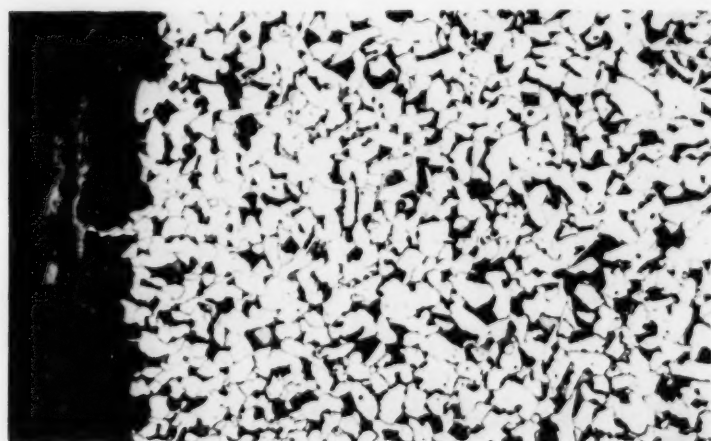
c. 1.5 percent sulfur refuse
1260 F



C4375

250X

b. Normal refuse
1235 F

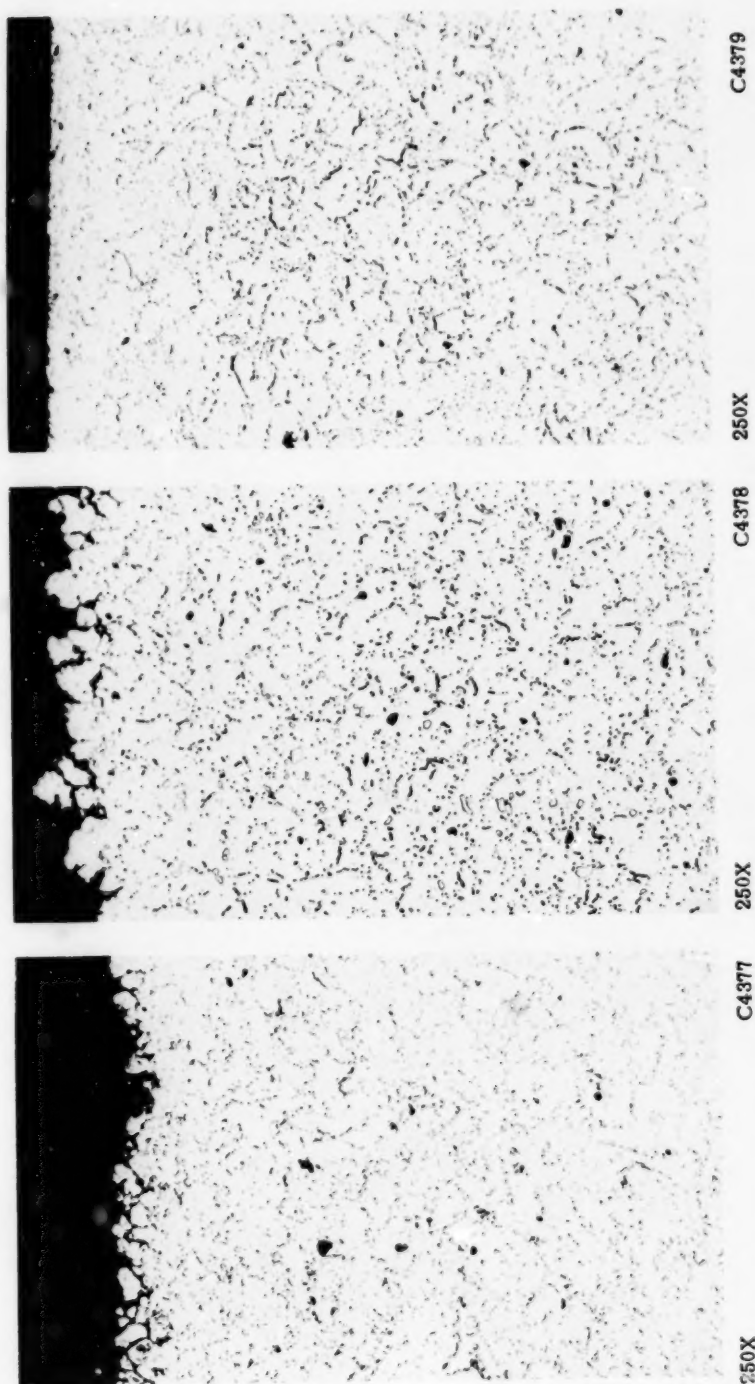


C4374

250X

a. Normal refuse
820 F

Figure 9. Photomicrographs of A106 steel showing mode of attack



c. 1.5 percent sulfur refuse

b. 2 Percent PVC refuse

a. Normal refuse

Figure 10. Photomicrographs of 446 steel showing mode of attack

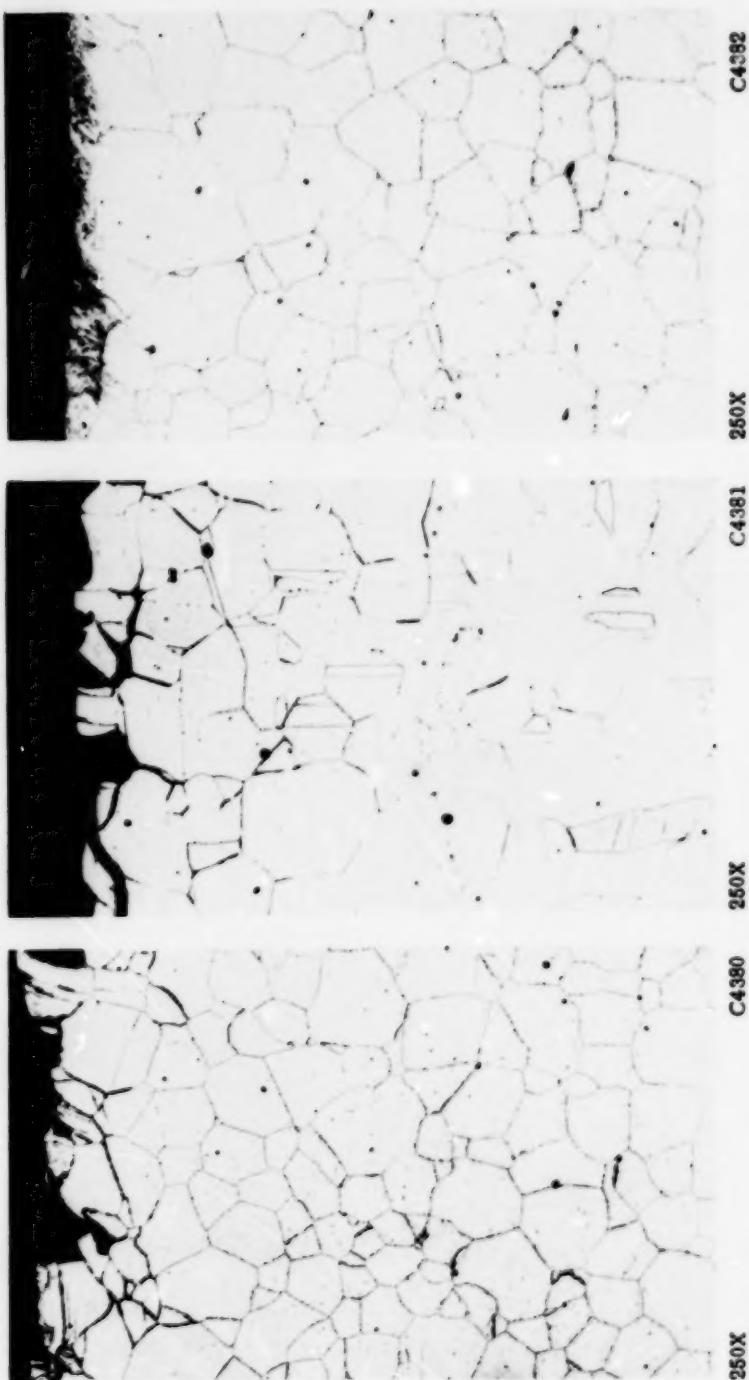
431 steel was evaluated in normal refuse and sulfur-doped refuse. This 16 percent Cr alloy was much less resistant to the combustion products of normal refuse than was the 27 percent Cr 446 alloy. The attack was of a general pitting type with little or no grain-boundary penetration. The addition of sulfur to the refuse reduced the attack of 431 steel by a factor of two - three.

316 and 302EZ stainless steels had very similar behavior in that they were attacked intergranularly by the combustion products of normal refuse and refuse to which PVC had been added. These steels were resistant and exhibited little or no grain-boundary attack when exposed to combustion products of the refuse with an increased sulfur content. Photomicrographs of 316 steel exposed to the various environments are shown in Figures 11a, b, and c.

310 stainless was exposed with and without PVC added to the refuse and exhibited the best resistance of the steels investigated. Photomicrographs of this steel after exposure are shown in Figures 12a and 12b. However, when this steel was exposed to the higher temperature furnaces gases, the attack increased and grain-boundary attack similar to that of 316 steel occurred. ¹Previously, it was shown that austenitic stainless steels cracked by stress corrosion when exposed to a humid environment in contact with combustion deposit.

321 stainless steel and Incoloy 825 were similar to 310 with only slight differences in magnitude of attack by the combustion products of normal refuse or PVC-doped refuse. These materials were not exposed to the combustion products of refuse with increased sulfur content.

Diffusion-bonded coatings of FeAl and Chromium on Al06 low-carbon steel were exposed to the combustion environment of normal refuse and high-sulfur refuse. In the case of the FeAl-coated specimens a solid-solution zone of ~10 mils was developed by the diffusion treatment. The excess FeAl was removed in most cases before exposing the specimen to the combustion environment. The resulting structure and mode of attack are shown in Figure 13a. In normal refuse-combustion environments there was considerable general surface attack, plus grain-boundary penetration to a depth of 6-8 mils. Similar attack occurred when sulfur was added to the refuse, but the magnitude of both types of attack was somewhat less. It is interesting to note that when the FeAl compound layer (50% Al 50% Fe) was not removed before exposure, the attack was very slight and an adherent oxide film formed on the surface.

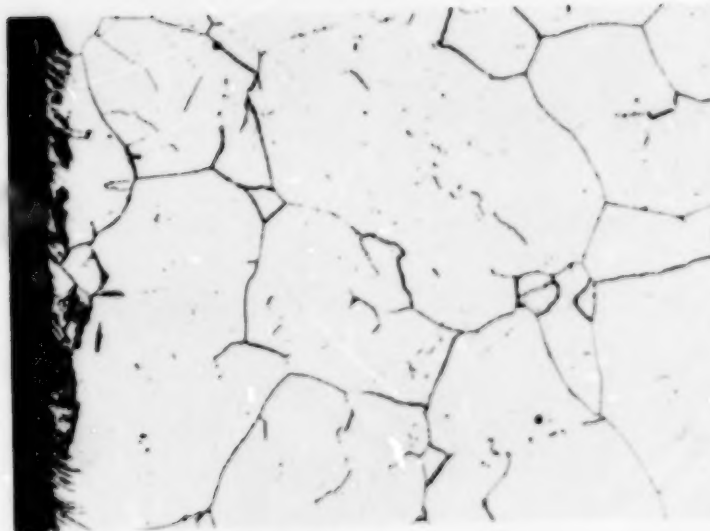


c. 1.5 percent sulfur refuse

b. 2 percent PVC refuse

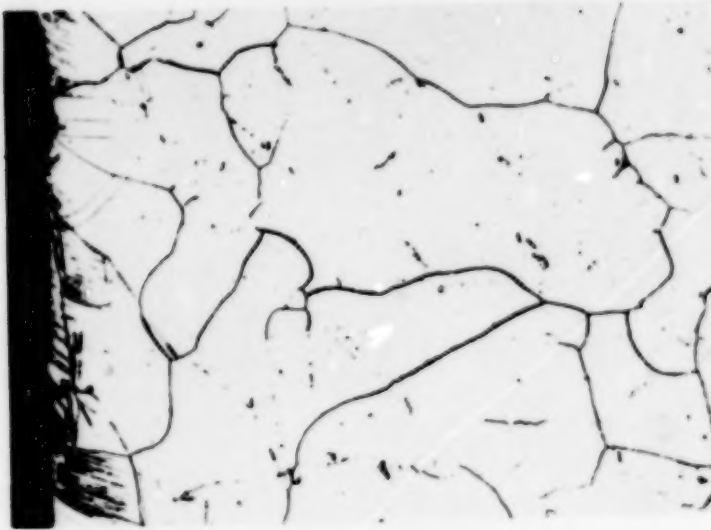
a. Normal refuse

Figure 11. Photomicrographs of 316 stainless steel showing mode of attack



250X

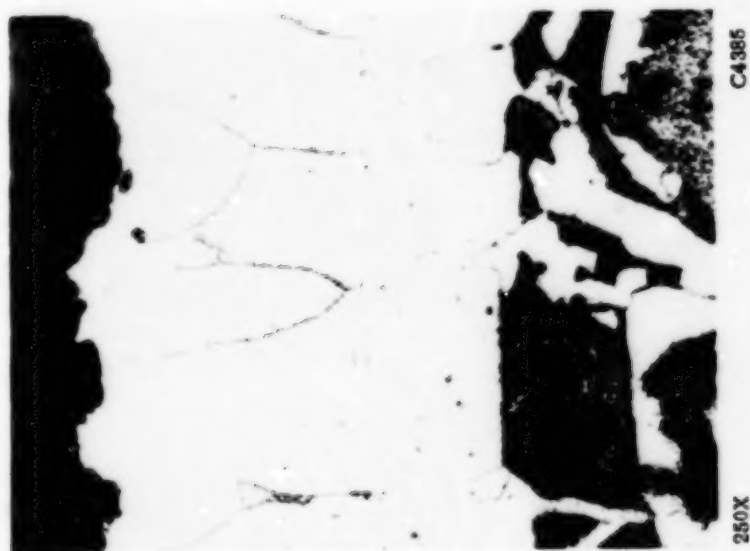
a. Normal



250X

b. 2 percent PVC refuse

Figure 12. Photomicrographs of 310 stainless steel showing mode of attack versus refuse composition



a. FeAl-coated A106 normal refuse



b. Cr-coated A106 0.75 percent sulfur refuse

Figure 13. Photomicrographs of diffusion-bonded coating on A106 steel after exposure to refuse combustion environments

The diffusion treatment of chromium-coated A106 steel produced a slight decarburization of the steel and an interface layer of chromium carbide between the substrate and the chromium coating. Although only slight attack of the chromium by the combustion environment was observed (Figure 13b), it is unlikely that the chromium layer would maintain adherence on this steel in extended exposure times. Perhaps this type of coating, if applied to another steel where the carbide interface did not form, would provide beneficial corrosion resistance to the refuse combustion environments.

DEPOSIT AND CORROSION PRODUCT ANALYSIS

As the corrosion probes were inserted into the fireside chamber of the incinerator above the effluent end of the grate, the airflow carried sufficient particulate matter to produce a deposit 1/4 to 1/2 inch thick over approximately one-third of the 1.25-inch-diameter tube in the 10-hour exposure periods. The remaining two-thirds of the surface contained only a thin deposit and an oxide layer, the oxide layer extending completely around the tube beneath the deposit. The thickness of the oxide layer varied for the various alloys and depended to some extent upon specimen temperature. These layers of deposit and oxide were removed mechanically and collected, by temperature zones, for optical emission spectroscopy analysis of the metallic element present. Wet chemical techniques were employed to determine the chlorine (Cl^-) and sulfur (SO_4^{2-}) content in the deposits. X-ray diffraction analyses were made of the deposit at one or two temperature zones on the probe. Also, the scales, which formed at the metal-deposit interface, were identified by X-ray diffraction and by optical microscopy examinations. The results of the analysis of the deposits obtained from runs with PVC additions to the refuse are presented in Table 4, in which averages for low- and high-temperature zones on each probe are given. Of particular interest is the increasing chloride content in the deposit with increasing PVC content of the refuse. It was noted, however, that the chloride content was somewhat low for Probes 17 and 20, which were exposed to a higher temperature furnace gas. Omitting the analyses for these two probes, the chloride content in the deposit versus PVC content of the refuse is illustrated in Figure 14. It is seen here that the chloride content of the deposit increases with PVC content of the refuse, but decreases with increasing metal temperature. As pointed out above, increasing the gas temperature also decreases the chloride content of the deposit.

Table 4. CHEMICAL ASSAY OF DEPOSITS VERSUS PVC ADDITION TO REFUSE

Elements detected	Probe 16, 0% PVC			Probe 19, 0.5% PVC			Probe 20, 0.5% PVC			Probe 18, 1% PVC			Probe 17, 2% PVC		
	400 F -	800 F -	1200 F -	400 F -	800 F -	1200 F -	400 F -	800 F -	1200 F -	400 F -	800 F -	1200 F -	400 F -	800 F -	1200 F -
Concentration, weight percent															
Na	7.5	7.5		6.9		7.5	6.9		7.5	6.5		4.5	5.0		4.0
K	11.5	19.0		3.7		3.6	4.4		3.7	10.8		7.5	8.5		8.0
Ca	6.0	7.5		6.4		12.5	6.7		12.5	10.8		12.5	7.5		10.0
Mg	2.0	3.0		1.0		2.0	0.6		2.0	3.3		3.0	2.5		3.5
Pb	2.5	1.0		3.2		0.3	3.1		0.3	3.0		0.3	2.0		0.5
Zn	6.0	6.5		6.9		7.5	6.9		7.5	6.5		4.5	6.0		4.5
Fe	5.0	6.0		12.3		7.1	12.6		6.6	8.5		6.3	6.5		6.0
Al	14.5	12.5		3.0		5.6	3.3		6.0	6.5		7.3	7.5		8.5
Si	4.5	5.5		3.4		7.5	3.9		7.5	7.5		7.5	6.0		6.5
Cl	4.0	1.5		7.6		3.6	4.8		1.9	5.8		1.3	11.5		4.5
S	8.0	9.0		7.8		8.3	4.9		7.6	6.9		8.6	6.5		5.5
O ₂															
Balance															
Phase studies in deposits															
--	CaSO ₄	CaSO ₄		CaSO ₄		CaSO ₄	CaSO ₄		CaSO ₄	--		--	CaSO ₄		CaSO ₄
	+	+		+		+	+		+				+		+
--	SiO ₂	Ca ₂ SiO ₄		Ca ₂ SiO ₄		Ca ₂ SiO ₄	--		SiO ₂	--		--	NaCl		NaCl
	+	+		+		+			+				+		+
--	K ₃ Na(SO ₄) ₂	NaCl		K ₃ Na(SO ₄) ₂		K ₃ Na(SO ₄) ₂	--		Ca ₂ SiO ₄	--		--	KCl		SiO ₂
													+		+
													SiO ₂		SiO ₂

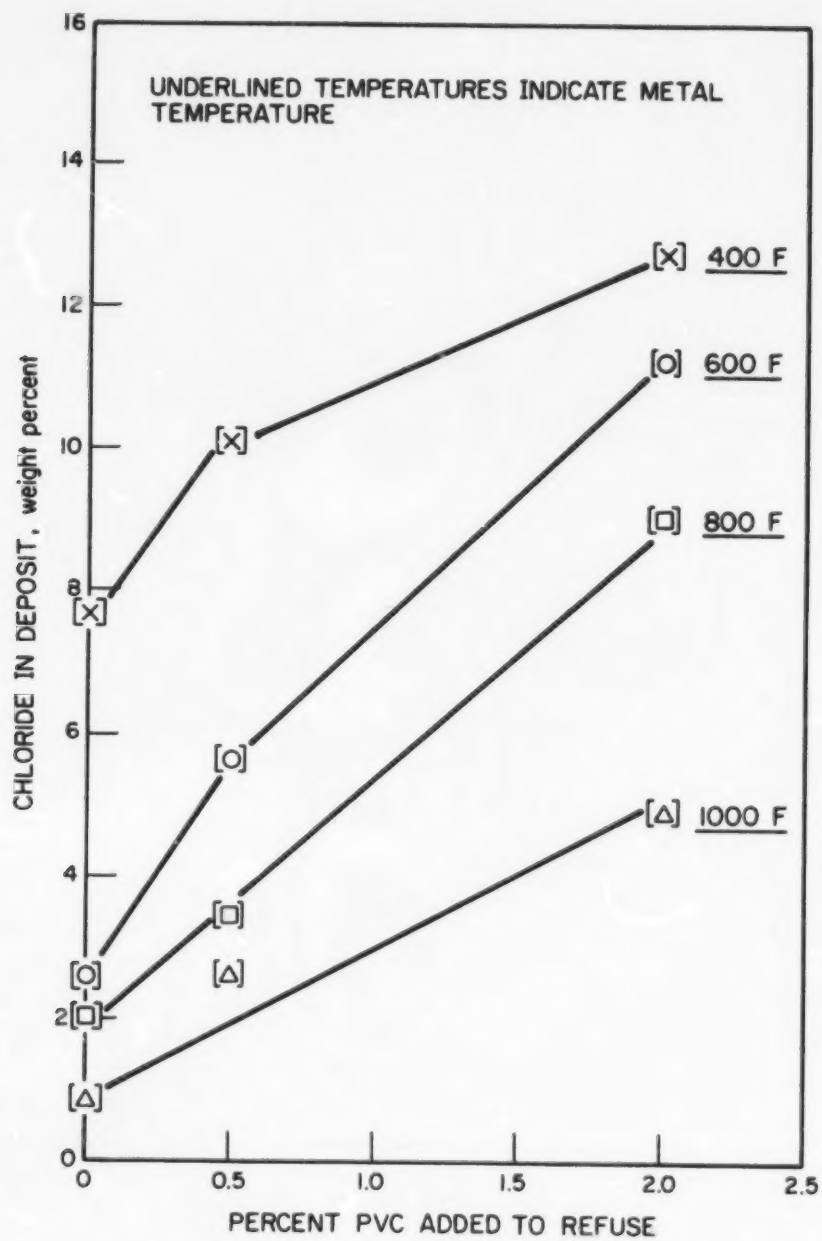


Figure 14. Chloride concentration in deposit versus amount of PVC added to refuse

Phase studies of these deposits by X-ray diffraction reveal (Table 4) sulfate, silicates, and chlorides; the intensity of the chloride phases increase with the amount of PVC added to the refuse. The chloride permeates the semiprotective oxide that forms between the deposit and the substrate metal and forms iron chloride on the substrate metal surface. The scale that forms next to the metal consists of the phases described in Table 5. When large amounts of PVC were added to the refuse, the iron chloride on specimens at temperatures of 400-800 F was found, by optical-microscopy examination, to form a continuous layer adjacent to the metal substrate. Optical-microscopy examinations show that the FeS reaction produce (Table 5) forms between the iron chloride layer and the oxide layer in the low-temperature (400-800 F) zone on the corrosion probe. The FeS forms on the metal substrate in the high-temperature (800-1200 F) zone where the iron chloride agglomerates to form islands on the metal surface. The FeS forms on the metal surface between the islands.

Table 5. PHASE STUDIES OF SCALE NEXT TO METAL

Probe number	Phases by layers between the metal and the oxide layer	
	400 F - 800 F	800 F - 1200 F
16	$\text{FeCl}_2 \cdot 4\text{H}_2\text{O} + \text{FeOOH} + \text{FeS}^c$	$(\text{FeCl}_2 \cdot 4\text{H}_2\text{O} + \text{FeOOH} + \text{FeS})^a$
17	$\text{FeCl}_2 \cdot 4\text{H}_2\text{O} + \text{KCl}$	$(\text{FeCl}_2 \cdot 4\text{H}_2\text{O} + \text{FeOOH} + \text{NaCl})^a$
18	As 17 - no evidence of sulfide layer ^b	As 17 ^b
19	$\text{FeCl}_2 \cdot 2\text{H}_2\text{O} + \text{FeCl}_2 \cdot 4\text{H}_2\text{O} + \text{FeOOH} + \text{FeS}^c$	$(\text{FeCl}_2 \cdot 2\text{H}_2\text{O} + \text{FeOOH} + \text{FeS})^a$
20	As 19	$(\text{FeCl}_2 \cdot 2\text{H}_2\text{O} + \text{FeS})^a$

^a Phases in this temperature zone do not form successive layers but are present in discrete areas.

^b Analyzed by optical method.

^c This FeS is found at the interface between the ferrous chloride and the oxide that separates the deposit from the scale.

The compositions of the deposits on probes exposed to combustion products of refuse with and without sulfur additions are presented in Table 6. There are fluctuations in the amounts of all elements present from one area to another in the deposit as well as from one probe to another. It is surprising, however, that the S^- content increased by only 1 percent when sulfur was added to the refuse. On the other hand, the Cl^- content decreased by nearly 5 percent, to less than 0.1 percent, with the addition of 1.5 percent sulfur. These data along with the corrosion-rate data, described previously, suggest that the corrosiveness of the incinerator combustion products varies directly with the Cl^- content of the resulting deposit. Presumably, the lack of an increase in S concentration in the deposit with increasing sulfur in the refuse is related to the type of

Table 6. CHEMICAL ASSAY OF DEPOSITS VERSUS
SULFUR ADDITION TO REFUSE

Probe no. - addition:	21-0% S		25-0.75% S		23-1.5% S	
Substrate temp, F:	745	1120	730	1125	740	1175
Elements Detected	Concentration, weight percent					
B	<0.1	0.1	<0.1	<0.1	<0.1	<0.1
Na	2.0	4.0	2.0	2.0	2.0	1.0
Mg	0.7	3.0	0.5	0.2	0.7	0.1
Al	2.0	4.5	3.0	4.5	2.0	4.5
Si	3.0	7.5	1.0	4.0	3.0	4.0
K	2.0	4.0	2.0	4.0	2.0	2.0
Ca	4.5	15.0	4.5	15.0	4.5	7.5
Ti	0.3	1.0	0.3	0.5	0.4	0.5
Cr	<0.1	2.0	0.1	0.1	<0.1	<0.1
Mn	0.2	0.3	0.2	0.3	0.3	0.5
Fe	25.0	15.0	25.0	15.0	20.0	15.0
Cu	<0.1	<0.1	0.1	0.1	0.1	0.2
Zn	3.0	3.0	3.0	2.0	7.5	3.0
Sn	0.1	0.1	0.3	0.1	0.3	0.1
Sb	<0.1	0.1	0.1	<0.1	<0.1	<0.1
Pb	0.4	0.1	1.5	0.3	2.5	1.5
Cl	7.5	2.5	1.9	0.1	0.1	<0.1
S	4.6	2.8	3.5	6.0	5.0	3.8
O ₂	Bal	Bal	Bal	Bal	Bal	Bal

compound formed. For example, the increase in some of the heavy metal elements, such as Pb and Zn, will result in a low weight percent of sulfur in the deposit. These heavy metal elements were found to be present in even higher concentrations in the fly ash particulates collected with the gas samples taken from the furnace and from the stack.

FURNACE AND STACK GAS ANALYSES

Standard EPA sampling trains consisting of probes, heated filters, and two or three impingers were used to collect furnace gas from an area near the corrosion probes for the HCl and the sulfur oxides analysis. During the experiment with PVC additions to the refuse, the HCl was collected in two impinger solutions each containing 100 milliliters of 5 weight percent NaOH, the analysis being done by titration with silver

nitrate after acidifying the solution. During the experiment with sulfur additions, the HCl was collected and analyzed in the same three solutions as the sulfur oxides. For sulfur oxides, the first impinger contained 100 milliliters of 80 percent isopropanol to absorb SO_3 . The other two impingers each contained 100 milliliters of 3 percent H_2O_2 to absorb SO_2 . Both SO_3 and SO_2 were then determined by titration of the respective absorption solutions with barium perchlorate, using thorin as the indicator. Particulates collected on the filters of the EPA train were analyzed by the same methods as those employed for the corrosion probe deposits.

Combustion gases (CO_2 , CO and O_2) were determined by standard Orsat methods or Fyrite analyzers. The water content was measured by condensing the moisture and determining its volume.

Nitrogen oxides were analyzed by collecting a sample of furnace gas in a 3-liter evacuated flask which contained 25 milliliters of 3 percent H_2O_2 acidified with H_2SO_4 and then using the standard phenol-disulfonic acid analysis method.

Furnace gas compositions are presented in Table 7. These results show rather large variations in HCl and sulfur oxide concentrations in the combustion gases, but the addition of either PVC or S did not produce proportionate changes in the respective gaseous species as was observed in the solid corrosion probe deposit. Thus, it is concluded that the gaseous species (HCl , SO_2 , and/or SO_3) react with various metal oxides, produced in refuse combustion to form inorganic salts. These salts may (1) form deposits, (2) be collected in the ash or scrubber system of the incinerator, or (3) be emitted with the stack gases.

Stack gas analyses were conducted for the experiments in which sulfur was added to refuse and the results are presented in Table 8. In contrast with the results of the furnace gas analyses, these results show a direct relationship between sulfur oxide content of the stack gas and the amount of sulfur added to the refuse. Although the HCl content of the stack gas appears to increase somewhat when sulfur is added to the refuse, the changes are within expected daily variations. However, the chloride content of the particulates appears to be markedly decreased when sulfur is added to the refuse.

Analyses of particulates collected in the filters of gas sampling trains are shown in Table 9. A comparison of these results with those for the corrosion probe deposits shows increases in the concentration of Na, K,

Table 7. INCINERATOR GAS ANALYSES

Additions to refuse ^a :	None		0.5% PVC	1.0% PVC	2.0% PVC	0.75% S	1.5% S
Experiment number:	72-16 ^b	73-21/22	72-19/20	72-18 ^b	72-17 ^b	73-26/26	73-23/24
Component analyzed	Parts per million						
HCl, ppm	374	147	583	904	862	58	210
SO ₂ , ppm	107	34	57	279	69	86	789
SO ₃ , ppm	13	2	8	13	9	3	8.6
NO _x , ppm	21	--	61	62	55	--	--
	Percent						
CO ₂ , percent	1.6	3.2	3.5	3.2	5.0	2.5	3.1
O ₂ , percent	18.2	17.1	17.2	14.5	16.2	17.0	17.5
H ₂ O, percent	18.5	--	5.3	10.8	7.4	--	--

^a For all experiments except 73-25/26 the refuse incinerated at Miami County was a mix of municipal and industrial waste with a ratio of 2/1. For experiment 73-25/26 the ratio was more nearly 10/1 as a large fraction of the industrial waste was being sent to landfill.

^b For these experiments the gas was collected at two times in 1-hour sampling each and the averages are reported. During the other experiments gas was sampled throughout the period of the corrosion experiment.

Table 8. STACK GAS ANALYSES

Addition to refuse ^a :	None	0.75% S	1.5% S
Experiment number:	73-21/22	73-25/26	73-23/24
Component analyzed	Parts per million		
HCL	52	108	114
SO ₂	51	424	1065
SO ₃	1.3	3.0	6.8

^a For all experiments except 73-25/26 the refuse incinerated at Miami County was a mix of municipal and industrial waste with a ratio of 2/1. For experiment 73-25/26 the ratio was more nearly 10/1 as a large fraction of the industrial waste was being sent to landfill.

Table 9. ANALYSIS OF PARTICULATES COLLECTED WITH FURNACE AND STACK GASES

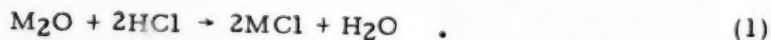
Addition to refuse: Experiment number: Location: Component analyzed	None 73-21/22		0.75% S 73-25/26		1.5% S 73-23/24	
	Stack	Furnace	Stack	Furnace	Stack	Furnace
	Concentrations, weight percent					
B	1.	<.1	<.1	<.1	<.1	<.1
Na	3. -5.	3. -5.	5. -10.	3. -5.	3. -5.	2. -4.
Mg	1.	1.	.1	.4	.1	.3
Al	1. -3.	3. -5.	.3	1.	.4	1.
Si	--	3. -6.	3.	1.	.2	1.
K	3. -6.	5. -10.	10. -20.	10. -20.	10. -15.	5. -10.
Cr	2.	3. -5.	.2	2.	.2	1.
Ti	<.1	1.5	<.1	.2	<.1	.3
Cr	<.1	<.1	<.1	<.1	<.1	<.1
Mn	T<.1	.1	T<.1	T<.1	T<.1	.1
Fe	.2	1.5	.2	.4	.2	.4
Cu	.1	.2	.1	.1	.1	.1
Zn	5. -15.	10. -20.	10. -20.	5. -15.	10. -20.	5. -15.
Sn	.6	.5	1. -3.	1. -3.	1. -3.	1.
Sb	.1	<.1	.1	.1	.1	<.1
Pb	2. -4.	1. -3.	5. -10.	5. -10.	5. -10.	3. -6.
Cl	28.8	--	12.1	3.3	0.74	8.1
SO ₂	12.4	--	12.0	7.2	28.7	17.7
O ₂	Bal	Bal	Bal	Bal	Bal	Bal

Zn, Sn, and Pb and decreases in Al, Si, Ca, Mn, and Fe for both the stack and furnace particulate samples. The compounds (calcium, aluminum silicates, and iron oxides) of the latter group of elements are more stable at the high furnace temperatures than are the compounds (potassium, lead, and zinc sulfates) of the former group of elements. Of particular interest are the Cl⁻ and S contents of the particulates collected with the gas samples; the S content shows a moderate increase with sulfur addition to the refuse while the Cl⁻ content shows a marked decrease. The latter was also observed for the tube deposits and is undoubtedly responsible for the sharp decrease in corrosion rate when sulfur is added to the refuse.

SECTION VI

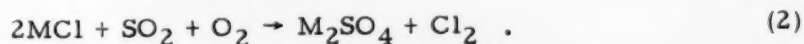
DISCUSSION OF RESULTS

The results of these investigations of refuse composition on fireside corrosion of heat-recovery tubes show strikingly opposite effects of changes in the chlorine and the sulfur content of refuse. An increase in the available chlorine, by the addition of PVC to the refuse, increases the corrosion rate of low-alloy steels, whereas the addition of sulfur to the refuse decreases the corrosion rate of all steels investigated by nearly an order of magnitude. The major contribution of these compositional variables to the corrosion reaction responsible for these changes in corrosion rates is in the type of compounds that deposit on the simulated heat-recovery tube, the corrosion probe. The analysis of probe deposits, particulates, and gaseous species shows that increasing the chlorine or sulfur contents in the refuse increases the amounts of these elements in the deposit and in extracted particulates in proportion to the amounts added. The SO_2 and SO_3 contents of the furnace and stack gases increase with sulfur addition to the refuse while the HCl content behaves in a sporadic manner. The corrosion rate and combustion product analyses reported herein confirm the importance of the chloride reaction described in References 1 and 13. It is evident, however, that the role of the HCl , generated by combustion of PVC, is to increase the inorganic (alkali) chlorides by the reaction:



The chlorides that deposit on the corrosion probes are mainly sodium and potassium salts, but also contain other metals such as lead and zinc. The mixture of these salts forms low-melting-point eutectic compositions that permeate and destroy the initial oxide scale that normally forms on metals exposed at the temperatures explored in this study. It is important to note that, although the metal temperatures were controlled, the deposits were exposed to much hotter incinerator

gases. The deposit temperatures were undoubtedly 300 F higher than the highest metal temperature. At the higher temperatures (1600 F), the chlorides decompose and/or react with other incinerator gases releasing chlorine which attacks the substrate metal. One of the possible reactions that would account for the production of chlorine is



In the present investigation, which was for short (10-hour) exposure times, the amount of chloride in the deposit with or without PVC additions was much larger than in a previous investigation¹ which was for long (100-800-hour) exposure times. The chloride content of the deposit was shown earlier,¹ however, to decrease with time. This would be expected through Reaction 2 above where the SO₂ content in the combustion products is low. Perhaps part of the reduction in corrosion rate with exposure time, as shown in Figure 1, results from the reduction in chloride content of the deposit with time. The short- and long-exposure time corrosion rates, shown in Figure 1, from Battelle corrosion probe experiments, are in good agreement with those of the superheater tubes which failed at the Harrisburg, Pennsylvania, incinerator. After 3000 hours of operation the 165-mil tubes failed in an area where the soot blower was used to remove the deposit and protective oxide scale at least daily. Thus the clean tube metal was exposed in much the same manner as the short-time (10-hour) exposure of the Battelle probes. The corrosion rate of 0.055 mil/hour at the Harrisburg tube failure is comparable to the 0.10 mil/hour corrosion rate obtained with normal refuse in the present study. In an area away from the soot blower, the Harrisburg tubes had lost ~15 mils in 3000 hour or 0.005 mil/hour which agrees quite well with the long-time (800-hour) Battelle data of 0.002 mil/hour.

Increasing the sulfur content of the refuse from the normal 0.2 percent level to 0.75 and 1.5 percent level increases the amount of SO₂ and sulfate compounds in the combustion products but reduces significantly the chloride content of the deposit on the corrosion probe or in the particulates extracted from the furnace or the stack. These observations show that, where sulfur oxides are present, the combustion process favors the formation of sulfates. The chlorine released by this reaction is believed to be in the form of HCl, Cl₂, or volatile chlorides which are easily removed from the stack gases by baffle scrubbers.

The lower corrosion rates observed when sulfur is added to the refuse show, as expected, that sulfates are more stable than are chlorides. However, it is important to note that with these sulfur additions sulfides did form near the metal-oxide interface beneath the deposit on all of the corrosion probe specimens. This is undoubtedly a result of the reducing environment beneath the oxide layer as it has been shown¹⁴ that FeS will form at very low sulfur pressure (10^{-13} atmosphere) if the SO₂ or O₂ pressures are below 10^{-14} atmosphere. At higher SO₂ or O₂ pressures iron oxides form. Several reactions have been proposed¹ for bisulfate, pyrosulfate, and alkali trisulfates attack of iron to give FeS. However, the present study has shown these reactions to be slow compared to the chloride reaction as the corrosion rates of steel exposed to the combustion product of high-sulfur refuse are very low (0.05 mil/hour) compared to those (0.15-0.20 mil/hour) of normal refuse or to the higher corrosion rates obtained when the PVC content of the refuse is increased. The very low corrosion rates of steels exposed to the combustion products of sulfur-enriched refuse are undoubtedly attributable to the low (0.1 percent) chloride content in the tube deposit. This is consistent with other data¹⁵ which show the negligible effect of this amount of chloride in Na₂SO₄ on the corrosion rate of a 18 Cr-12 Ni-1Nb steel. In these and most other investigations of reaction between metals and inorganic compounds, the specimens are at the same temperature as the environment. However, in the case of heat-recovery tubes the furnace temperature is considerably higher than the tubes, in which case deposit decomposition reactions become important. The present study has shown further that a significant increase in corrosion rates of metals occurs when the furnace-gas temperature is increased from 1400 F to 1550 F. This is particularly evident for metal temperatures above 800 F, but laboratory investigations under more controlled conditions are needed to evaluate this effect in more detail.

SECTION VII

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SECTION VIII

APPENDICES

APPENDIX A

CORROSION-PROBE DATA

Each specimen of the corrosion probe was weighed to the nearest 0.1 milligram before assembly of the probe and again after exposure and removal of the deposit and scale, as described in the text of this report. The loss in weight resulting from the attack by the incinerator combustion product environment was assumed to be uniform even though some pitting was observed in the area under the deposit for some alloys. This weight loss was then converted to a thickness in mils over the 5.88 square inches of exposed surface. For steel, the weight loss per mil removed over this area is 0.762 gram, or 1.31 mils wastage per gram of weight loss. The internal surface is exposed to cooling air, and the weight loss is less than 0.002 gram even at the hot end of the corrosion probe. Thus, the loss in weight by oxidation internally is very small compared with the total loss, and was therefore disregarded in the analysis, as presented in Tables 10 and 11.

TABLE 10. CORROSION DATA VERSUS PVC ADDITIONS

Specimen	Probe 16, 0% PVC			Probe 19, 0.5% PVC			Probe 20, 0.5% PVC		
	Wt loss	Mils	Mils/hr	Temp. F	Specimen	Wt loss	Mils	Mils/hr	Temp. F
1 - A106	0.2745	0.362	0.0362	295	A106	0.627	0.827	0.0827	300
2 - T11	0.4083	0.538	0.0538	350	T11	1.093	1.44	0.144	315
3 - A106	1.4472	1.62	0.162	415	A106	1.302	1.72	0.172	355
4 - T11	0.7599	1.002	0.100	475	T11	1.489	1.97	0.197	390
5 - A106	0.9053	1.194	0.119	535	A106	1.421	1.87	0.187	410
6 - T11	0.8439	1.120	0.112	536	T11	1.442	1.93	0.193	455
7 - A106	1.5182	2.00	0.200	650	A106	1.640	2.16	0.216	490
8 - T11	0.9720	1.283	0.128	715	T11	1.729	2.28	0.228	515
9 - A106	1.2844	1.69	0.169	775	A106	1.721	2.27	0.227	545
10 - T11	1.1613	1.53	0.153	833	T11	1.884	2.48	0.248	570
11 - A106	1.2961	1.72	0.172	860	A106	1.008	1.41	0.141	610
12 - T11	1.3366	1.77	0.177	875	T11	0.764	1.01	0.101	670
13 - A106	1.2554	1.66	0.166	910	A106	2.182	2.84	0.284	715
14 - T11	1.4435	1.90	0.190	930	T11	1.866	2.46	0.246	765
15 - A106	1.4971	1.98	0.198	955	A106	2.201	2.90	0.290	815
16 - T11	1.7879	2.32	0.232	980	T11	2.036	2.76	0.276	865
17 - A106	1.7659	2.33	0.233	1005	A106	2.209	2.92	0.292	910
18 - T11	2.0885	2.76	0.276	1030	T11	2.297	3.02	0.302	950
19 - A106	1.7097	2.25	0.225	1055	A106	1.882	2.48	0.248	1010
20 - T11	2.3224	3.06	0.306	1065	T11	2.196	2.89	0.289	1015
21 - 446	0.3239	0.427	0.0427	1075	446	0.138	0.182	0.0182	1020
22 - 310	0.1916	0.253	0.0253	1085	310	0.192	0.253	0.0253	1025
23 - 316	0.4415	0.582	0.0582	1095	316	0.897	1.18	0.118	1030
24 - 321	0.5295	0.699	0.0699	1105	321	1.038	1.37	0.137	1040
25 - 446	0.3883	0.512	0.0512	1115	825	0.374	0.494	0.0494	1050
26 - 310	0.2200	0.290	0.029	1125	310	0.210	0.277	0.0277	1055
27 - 316	0.5114	0.675	0.0675	1135	T11	2.581	3.41	0.341	1065
28 - 321	0.5842	0.770	0.077	1145	A106	2.071	2.73	0.273	1070
29 - Incoloy (825)	0.5047	0.666	0.0666	1155	825	0.386	0.509	0.0509	1075
30 - 446	0.3482	0.459	0.0459	1165	446	0.205	0.270	0.0270	1080
31 - 310	0.1230	0.162	0.0162	1175	310	0.211	0.278	0.0278	1090
32 - 316	0.5999	0.790	0.0790	1185	316	0.963	1.27	0.1270	1095
33 - 321	0.6180	0.815	0.0815	1195	321	1.092	1.49	0.149	1100
34 - 446	0.3967	0.523	0.0523	1205	446	0.254	0.336	0.0336	1110

TABLE 10. (Continued)

Probe 18, 1% PVC				Probe 17, 2% PVC					
Specimen	Wt loss	Mils	Mils/hr	Temp. F	Specimen	Wt loss	Mils	Mils/hr	Temp. F
1 - A106	0.6220	0.820	0.078	240	A106	0.4507	0.595	0.0595	290
2 - T11	2.0244	2.675	0.25	315	T11	1.2983	1.719	0.1719	340
3 - A106	1.6850	2.224	0.21	380	A106	1.7134	2.262	0.2262	400
4 - T11	2.3238	3.0800	0.293	450	T11	1.9157	2.530	0.2530	455
5 - A106	1.8070	2.400	0.23	510	A106	1.7214	2.278	0.2278	510
6 - T11	2.2170	2.930	0.279	575	T11	1.8206	2.404	0.2404	565
7 - A106	1.8384	2.427	0.23	640	A106	2.3109	3.05	0.305	620
8 - T11	2.4106	3.180	0.303	700	T11	1.9210	2.538	0.2538	680
9 - A106	2.2044	2.910	0.277	770	A106	1.8163	2.400	0.240	780
10 - T11	2.7233	3.600	0.34	835	T11	2.1855	2.890	0.289	790
11 - 446	0.8068	1.064	0.101	865	446	0.5740	0.756	0.0756	810
12 - 825	0.6022	0.795	0.0757	900	825	0.1579	0.208	0.0208	840
13 - A106	3.2005	4.225	0.401	925	A106	2.1635	2.850	0.2850	865
14 - T11	3.9374	5.1968	0.495	960	T11	2.6657	3.510	0.3510	890
15 - A106	2.3386	3.085	0.293	990	A106	2.3863	3.146	0.3146	920
16 - T11	3.4413	4.540	0.434	1020	T11	3.0671	4.050	0.4050	950
17 - A106	3.0801	4.066	0.386	1050	A106	3.1632	4.175	0.4175	975
18 - T11	4.4400	5.800	0.55	1080	T11	3.5317	4.660	0.4660	1000
19 - A106	3.1230	4.125	0.392	1110	A106	2.8262	3.739	0.3739	1020
20 - T11	4.6255	6.100	0.58	1135	T11	3.4149	4.500	0.4500	1040
21 - 446	2.0283	2.680	0.256	1140	446	0.4671	0.616	0.0616	1050
22 - 310	1.1892	1.570	0.150	1150	310	0.3516	0.464	0.0464	1055
23 - 316	1.5135	1.945	0.19	1160	316	0.4962	0.655	0.0655	1060
24 - 321	1.6821	2.219	0.211	1170	321	0.8376	1.106	0.1106	1070
25 - 825	1.9458	2.570	0.247	1185	825	0.4489	0.591	0.0591	1080
26 - 310	1.3697	1.807	0.172	1200	310	0.3299	0.435	0.0435	1090
27 - T11	4.5741	6.040	0.574	1210	316	0.4941	0.652	0.0652	1100
28 - A106	3.5071	4.630	0.442	1220	A106	4.200	5.550	0.5550	1105
29 - 825	1.8301	2.415	0.23	1235	825	0.4171	0.551	0.0551	1115
30 - 446	1.8234	2.410	0.23	1250	446	0.4199	0.554	0.0554	1120
31 - 310	1.1256	1.479	0.141	1260	310	0.3534	0.466	0.0466	1130
32 - 316	1.0859	1.440	0.137	1275	316	0.6467	0.855	0.0855	1145
33 - 321	1.2550	1.655	0.158	1285	321	1.0482	1.385	0.1385	1150
34 - 446	0.9072	1.275	0.122	1295	446	0.8384	1.108	0.1108	1155

TABLE 11. CORROSION DATA VERSUS SULFUR ADDITIONS

Specimen	Probe 21, 0% S			Temp. F	Probe 22, 0% S			Temp. F	Probe 25, 0.75% S			Temp. F
	Wt loss	Mils	Mils/hr		Wt loss	Mils	Mils/hr		Wt loss	Mils	Mils/hr	
1 - A106	0.2742	0.362	0.06	240	0.659	0.87	0.14	390	0.2974	0.3925	0.0654	360
2 - A106Al	1.7041	2.25	0.37	360	0.9464	1.25	0.21	480	0.6338	0.8366	0.1394	420
3 - 203EZ	1.3705	1.81	0.30	455	0.5156	0.68	0.11	550	0.1825	0.2409	0.0402	475
4 - 431	1.2431	1.64	0.27	525	2.3206	3.07	0.51	620	0.1579	0.2084	0.0347	530
5 - 446	0.3966	0.524	0.09	600	0.2752	0.363	0.06	685	0.1600	0.2112	0.0352	580
6 - A106CR	0.386	0.558	0.09	650	0.0760	--	--	730	0.3935	0.5194	0.0866	630
7 - 316ST	0.3647	0.48	0.08	700	0.1937	0.256	0.043	780	0.0194	0.0256	0.0043	660
8 - A106	1.2172	1.60	0.27	745	--	--	--	820	1.1189	1.477	0.2462	730
9 - A106Al	0.5025	0.66	0.11	780	0.7267	0.96	0.16	850	1.0171	1.3426	0.2238	765
10 - 203EZ	0.7045	0.93	0.15	810	0.3915	0.516	0.086	870	0.1566	0.2067	0.0344	790
11 - 431	0.3634	0.479	0.08	825	1.1685	1.54	0.257	890	0.1107	0.1461	0.0244	815
12 - 446	0.3248	0.428	0.07	845	0.2361	0.312	0.052	910	0.0886	0.1170	0.0195	830
13 - A106CR	0.5882	0.838	0.14	860	0.6367	0.918	0.16	930	0.1258	0.1661	0.0277	850
14 - 316ST	0.3289	0.434	0.072	875	0.4616	0.61	0.10	950	0.0195	0.0257	0.0043	865
15 - A106	1.7178	2.26	0.38	885	2.1776	2.87	0.46	970	1.0662	1.407	0.2346	880
16 - A106Al	0.5654	0.745	0.124	900	--	--	--	985	--	--	--	900
17 - 203EZ	0.8485	1.118	0.186	915	0.6965	0.919	0.153	1005	0.1735	0.2290	0.0382	915
18 - 431	0.6474	0.855	0.142	935	0.7507	1.00	0.17	1025	0.1051	0.1387	0.0231	930
19 - 446	0.2996	0.395	0.066	955	0.4237	0.559	0.093	1045	0.0832	0.1098	0.0183	950
20 - A106CR	0.125	0.18	0.03	975	0.5507	0.794	0.15	1065	0.2622	0.3461	0.0577	970
21 - 316ST	0.9207	1.218	0.203	990	0.7989	1.052	0.175	1080	0.0423	0.0558	0.0093	985
22 - A106	1.1109	1.47	0.24	1005	3.1211	4.12	0.69	1100	1.2036	1.5888	0.2643	1005
23 - 203EZ - A106Al	0.7232	0.95	0.16	1015	2.7632	3.66	0.61	1120	--	--	--	1020
24 - 203EZ	0.7699	1.015	0.17	1030	--	--	--	1140	0.1859	0.2454	0.0409	1040
25 - 431	--	--	--	1050	--	--	--	1155	0.2276	0.3004	0.0501	1055
26 - 446	0.5685	0.751	0.142	1065	0.1276	0.168	0.028	1175	0.1819	0.2401	0.0400	1070
27 - A106CR	0.872	1.24	0.21	1080	0.5988	0.862	0.16	1195	0.4036	0.5328	0.0888	1090
28 - 316ST	1.0170	1.34	0.22	1100	1.0041	1.33	0.22	1215	0.0444	0.0586	0.0098	1110
29 - A106	1.9306	2.55	0.43	1120	4.1259	5.44	0.91	1235	1.5900	2.0988	0.3498	1125
30 - A106Al	1.5045	1.93	0.32	1135	2.4739	3.26	0.54	1255	--	--	--	1140
31 - 203EZ	0.8993	1.188	0.198	1150	0.7523	0.944	0.166	1275	0.2140	0.2825	0.0471	1160
32 - 431	0.9451	1.250	0.208	1165	0.7002	0.925	0.184	1290	0.2549	0.3365	0.0563	1180
33 - 446	--	--	--	1190	--	--	--	1310	0.1038	0.1370	0.0228	1195
34 - A106CR	1.204	1.74	0.24	1210	0.752	1.06	0.18	1330	0.3322	0.4385	0.0731	1210

TABLE 11. (Continued)

Specimen	Probe 26, 0.75% S				Probe 23, 1.5% S				Probe 24, 1.5% S			
	Wt loss	Mils	Mils/hr	Temp. F	Wt loss	Mils	Mils/hr	Temp. F	Wt loss	Mils	Mils/hr	Temp. F
1 - A106	0.8120	1.0718	0.1786	360	0.0918	0.121	0.02	410	0.3852	0.508	0.084	570
2 - A106A1	--	--	--	420	0.1935	0.255	0.042	470	--	--	--	610
3 - 203EZ	0.2718	0.3588	0.0598	470	0.0277	0.0366	0.006	520	0.0819	0.1082	0.0181	650
4 - 431	0.3160	0.4171	0.0635	530	0.0747	0.0458	0.007	570	0.0842	0.1110	0.0185	690
5 - 446	0.2391	0.3156	0.0526	580	0.0153	0.0202	0.003	620	0.0644	0.085	0.014	720
6 - A106CR	0.8643	1.409	0.1902	640	0.0308	0.044	0.007	660	0.0755	0.109	0.018	755
7 - 316ST	0.1019	0.1345	0.0224	635	--	--	--	700	0.0504	0.0665	0.011	790
8 - A106	1.6156	2.1326	0.3554	750	0.3548	0.473	0.077	740	--	--	--	825
9 - A106A1	--	--	--	800	0.1345	0.177	0.029	770	0.4924	0.650	0.11	860
10 - 203EZ	0.2117	0.2794	0.0466	825	0.0854	0.113	0.018	800	0.0939	0.1238	0.0206	880
11 - 431	0.1932	0.2550	0.0425	850	0.0455	0.060	0.010	825	0.1250	0.0275	0.0095	905
12 - 446	0.3048	0.4023	0.0671	875	0.0166	0.0219	0.003	850	0.0435	0.0575	0.0096	930
13 - A106CR	0.6865	0.9088	0.1515	900	--	--	--	890	0.0946	0.1362	0.023	955
14 - 316ST	0.0931	0.1229	0.0205	925	0.0405	0.0535	0.009	915	0.0648	0.0855	0.014	985
15 - A106	1.8120	2.3918	0.3986	950	0.4149	0.546	0.091	935	0.7352	0.970	0.16	1010
16 - A106A1	--	--	--	975	0.0294	0.038	0.006	960	0.0788	0.107	0.017	1030
17 - 203EZ	0.1966	0.2595	0.0433	1000	0.0980	0.1293	0.021	980	0.1059	0.1398	0.0233	1050
18 - 431	0.2207	0.2913	0.0486	1025	--	--	--	1000	0.1100	0.1452	0.0242	1070
19 - 446	0.1782	0.2352	0.0392	1050	0.0197	0.026	0.004	1020	0.0790	0.104	0.017	1090
20 - A106CR	0.8173	1.0789	0.1798	1080	0.0498	0.0711	0.012	1040	0.1515	0.218	0.036	1110
21 - 316ST	0.1264	0.1608	0.0278	1105	0.0587	0.0775	0.013	1060	0.187	0.247	0.041	1135
22 - 2016	2.7128	3.5803	0.5968	1130	0.5495	0.725	0.121	1080	1.3814	1.822	0.304	1155
23 - A106A1	--	--	--	1155	0.2023	0.267	0.045	1100	0.2478	0.326	0.054	1175
24 - 203EZ	0.3979	0.5160	0.0860	1180	0.3114	0.410	0.068	1115	--	--	--	1190
25 - 431	0.4651	0.6139	0.1023	1205	0.0608	0.0802	0.013	1125	0.3945	0.5210	0.0868	1210
26 - 446	0.2940	0.3841	0.0640	1230	--	--	--	1140	0.0491	0.064	0.011	1220
27 - A106CR	--	--	--	1250	0.2630	0.347	0.058	1150	0.0675	0.097	0.016	1230
28 - 316ST	0.2596	0.3427	0.0571	1260	0.1292	0.1705	0.028	1165	0.3736	0.492	0.082	1245
29 - A106	4.8250	6.3690	1.0615	1270	0.9685	1.278	0.213	1175	1.4191	1.871	0.312	1260
30 - A106A1	--	--	--	1275	0.3546	0.407	0.078	1190	0.8103	1.070	0.16	1280
31 - 203EZ	0.4789	0.6321	0.1054	1280	0.4650	0.614	0.102	1200	0.5189	0.684	0.114	1290
32 - 431	0.6362	0.8398	0.1400	1285	0.2568	0.339	0.056	1210	0.5201	0.687	0.1145	1300
33 - 446	0.3890	0.5135	0.0856	1290	0.0390	0.0515	0.008	1220	0.0614	0.088	0.015	1310
34 - A106CR	1.4162	1.8694	0.3116	1300	0.1169	0.1543	0.026	1230	--	--	--	1320

APPENDIX B

ANALYSES OF TYPE AND COMPOSITION OF REFUSE

The heterogeneous nature of the refuse burned at the Miami County incinerator results from the sources which include a number of industries plus municipal refuse from surrounding communities. The ratio of municipal to industrial refuse received for the week of June 26, 1972, was 2.08 with a total 378 tons (593 tons' municipal and 285 tons' industrial). As the amount of each received differs daily, the M/I ratio varied from 0.65 to 4.42. Wednesday, June 28, 1972, had nearly the maximum in the amount (187 tons) received and the M/I ratio was 2.03. Based upon this inspection of the records at the Miami County incinerator, Wednesday was selected as the day of the week to conduct corrosion experiments to evaluate the effect of PVC on the corrosion of waterwall materials.

The program consisted of four runs with five corrosion probes and exposure times of 10 hours each. The refuse received on the days of these runs is tabulated below:

No.	Day	Weight of refuse, tons			
		Municipal	Industrial	Total	Ratio
16	8/9/72	117.5	53.5	171.0	2.10
17	9/13/72	82.5	57.0	189.5	1.45
18	10/25/72	86.5	62.0	148.5	1.40
19/20	12/13/72	110.0	40.5	150.5	2.72

As the incinerator operates on a 24-hour-a-day basis, approximately 10/24 of the refuse received was burned during the 10-hour exposure period. No PVC was added during Run 16 to provide baseline corrosion-rate data for these short-time experiments. For Runs 17, 18, and 19/20, PVC was added to each grapple load fed into the incinerator. Approximately 160 grapple loads were fed into the incinerator in the 10-hour exposure periods. As a grapple load weighs ~1000 pounds, the

amounts of PVC added were 20 pounds (2 percent), 10 pounds (1 percent), and 5 pounds (1/2 percent) per grapple load for the Runs 17, 18, and 19/20, respectively.

In addition to the above categorization of refuse, Mr. R. Thurnau and Mr. R. Loebker, with the assistance of various Battelle staff, made a hand sort of grab samples taken on each of the above dates. These grab samples were taken at approximately 10:00 a.m. from the refuse pit by the crane operator and placed on the floor adjacent to the pit. The refuse was sorted into 12 categories, weighed, and percentages calculated as shown in Table B12. The total weight of the grab samples ranged from 303 to 785 pounds (0.2-0.5 percent of the refuse burned in 10 hours). A small but proportional amount of each category was taken to the Solid Waste Research Laboratory in Cincinnati for analysis. The categories were remixed and ground to 4.0- and 0.5-millimeter particles for analysis of the following properties:

- (1) Moisture content
- (2) Ash content
 - (a) Composition of ash
- (3) Volatiles content
 - (a) Composition of volatiles
- (4) Heat content.

The results of these analyses, as presented in Table B13, were supplied by Mr. Loebker except for the element analyses on the ash which were made at Battelle by optical emission spectroscopy (OES). The amounts of the various elements found in the ash are very similar to alkali metal content to that found in the deposit (see Table 4 of this report). However, the deposits had significantly higher concentrations of iron, zinc, and lead and considerably more chloride and sulfate than the ash. This suggests that the cold wall of the corrosion probe tends to preferentially retain some materials. The higher iron content in the deposit is probably due to oxidation of the probe.

Table 12. TYPE OF REFUSE IN GRAB SAMPLE
(percent)

Category	Run 16 Aug. 9, 1972		Run 17 Sept. 13, 1972		Run 18 Oct. 25, 1972		Run 19-20 Dec. 13, 1972		Other Investigation ^b
	Wet	% H ₂ O ^a	Wet	% H ₂ O ^a	Wet	% H ₂ O ^a	Wet	% H ₂ O ^a	
Cloth	2.07	32.81	2.53	25.48	1.75	10.54	2.1	21.10	2.9
Plastic	3.06	28.35	5.57	14.08	4.59	16.14	2.6	17.44	2.4
Food	17.78	54.56	3.08	58.91	15.25	66.44	9.1	59.13	10.6
Yard and garden	10.00	62.53	0.04	----	18.10	58.37	1.4	39.05	5.7
Wood	5.29	7.60	2.76	11.92	1.06	12.27	5.4	19.13	3.4
Paper	20.58	36.65	62.05	30.90	24.48	34.84	35.5	25.95	26.2
Corrugated paper boxes	13.82	14.61	5.79	29.62	4.27	26.00	2.0	16.08	13.1
Newspaper	2.55	15.18	2.30	39.35	9.4	41.15	11.9	16.04	11.4
Metal	12.87	9.42	6.19	1.95	7.49	8.43	6.4	3.47	8.5
Glass	8.60	0.22	4.16	1.37	5.97	1.95	8.4	0.37	9.4
Magazines	0.76	10.30	1.56	19.48	1.19	11.73	6.1	7.65	Included with paper
Fines	2.61	43.07	4.98	25.46	6.39	32.71	9.1	35.50	6.6
Total Weight of Grab, in lb	784.7	29.94	642.25	26.81	544.2	36.59	303.0	23.59	

^a Percent loss on heating at 100 C.

^b Average of Kaiser 1968, 1972, and Drobny 1971 data, normalized.

Note: All weightings were read to the nearest 1/4 pound.

Table 13. ANALYSIS OF REMIXED AND GROUND REFUSE FROM GRAB SAMPLE

Analysis as indicated, %	Run 16		Run 17		Run 18		Run 19/20		Remarks
	4 mm	0.5 mm	4 mm	0.5 mm	4 mm	0.5 mm	4 mm	0.5 mm	
Moisture	29.94		26.81		36.59		23.59		L-O-100 C
Ash	15.10	16.37	10.24	11.69	7.62	--	5.86	6.05	LOI (960 C)
Si in Ash		16.2		12.1		10.0		6.2	LOI (500 C)
Ca in Ash		10-20		10-20		10-20		10-20	OES
Na in Ash		5-10		5-10		10-20		5-10	OES
K in Ash		2-4		5-10		3-6		3-6	OES
Al in Ash		2-4		2-4		3-6		3-6	OES
Mg in Ash		3-6		5-10		3-6		10-20	OES
Fe in Ash		1-2		2-4		2-4		1-2	OES
Ti in Ash		3-5		3-5		1-2		1-2	OES
Pb in Ash		2.0		3.0		1.0		1-2	OES
Zn in Ash		0.3		0.4		0.2		0.4	OES
Cu in Ash		0.4		0.2		0.1		0.3	OES
Mn in Ash		0.2		0.2		0.2		0.2	OES
Ba in Ash		0.2		0.1		0.1		0.05	OES
Cr in Ash		0.3		0.1		0.3		0.1	OES
Zr in Ash		0.04		0.04		0.04		0.07	OES
Sn in Ash		0.02		0.04		0.01		0.01	OES
Ni in Ash		0.02		0.02		0.01		0.01	OES
Mo in Ash		0.005		0.02		0.005		0.005	OES
Cl in Ash		0.005		0.005		0.005		0.007	OES
Loss on ignition	0.011	0.006	0.020	0.018	---	---	---	---	Solid Waste Laboratory
C (in dry sample)	84.90	83.63	89.76	88.31	92.38	---	94.14	93.95	Solid Waste Laboratory
H	42.92	41.82	45.06	42.94	48.19	---	47.24	45.93	Solid Waste Laboratory
N	5.60	5.46	6.13	5.76	6.47	---	6.37	6.14	Solid Waste Laboratory
Cl	0.57	0.78	0.54	0.56	0.91	---	0.75 ^b	---	Solid Waste Laboratory
S	0.54	0.44	0.79	0.70	0.32	0.36	0.37	0.38	Solid Waste Laboratory
O ₂	0.20		0.20		0.20		0.20		Based upon other refuse ^a
Btu/lb	35.1	34.9	37.0	38.2	36.28	---	39.21	40.55	By difference
	7691	7548	8083	7742	8886	---	8523	8164	

^a Twenty-one other samples gave S contents of 0.10 to 0.37 percent, averaging 0.19 percent.^b Estimated on basis of average for similar samples.